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THE DIMENSIONAL STABILITY ANALYSIS

OF SEVENTEEN STEPPED SPECIMENS OF

18Ni 200 GRADE, PH13-8Mo, AND A-286

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D. A. Wigley

KENTRON INTERNATIONAL, INC.
Hampton Technical Center
Hampton, Virginia 23666

AC & MC
Applied Cryogenics and Materials Consultants
New Castle, DE 19720

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Langley Research Center
Hampton, Virginia 23665

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The Dimensional Stability Analysis of Seventeen Stepped Specimens of
18Ni 200 Grade, PH13-8Mo, and A286

1. Introduction

The use of a simple stepped specimen configuration to generate data on the dimensional stability of candidate materials for cryogenic wind tunnel models was developed jointly by the author of this report and Langley Research Center (LaRC) in January 1987. The results of initial tests on a 18Ni 200 Grade sample carried out in collaboration with the Gas Bearings Advisory Service of the University of Southampton, England, were reported briefly at the Cryogenic Models Workshop held at LaRC on May 5th-6th, 1982 (Ref.1). A more detailed description of these results and their analysis is contained in a subsequent high number contractor report submitted in August 1982 (Ref.2).

In view of the apparent urgency to the Cryogenic Models program of obtaining information on the stability of three materials which were already being used for model fabrication at LaRC, 18Ni 200 Grade, PH13-8Mo, and A286, instructions were issued for a total of seventeen stepped specimens to be fabricated and validated either by LaRC personnel or by their local subcontractors. Specimens were cut from either the surface or the center of plate stock and were orientated with the steps either parallel or perpendicular to the major rolling direction. In an attempt to see whether the fabrication sequence was important, some samples were heat-treated before rough machining, while others were heat treated after rough machining. Finally, all samples were submitted to cryogenic temperature cycles to establish their dimensional stability in what would be the working environment of a model in a cryogenic wind tunnel.

In this report, the results obtained from these 17 specimens are presented in a form that it is hoped the reader will find easy to assimilate and thus follow the changes in profile of the reference surface, from one validation stage to the next. Additional information obtained at Southampton, using the same techniques as those utilized in the original 18Ni 200 Grade sample (Ref.1), is also presented in order to give a cross-check between the two sets of measurements.

These results are then reviewed in order to see whether or not it is possible to establish any significant trends in the behaviour of the different materials, the location of the samples, or the relative sequence of the fabrication stages.

Finally, recommendations are made on where improvements may be instigated in order to ensure greater control over the fabrication and validation stages and thus enable more meaningful data to be obtained from the stepped specimen program.

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2. Fabrication and Validation Processes Laid Down for the Seventeen Specimens

2.1 Fabrication

The basic configuration and dimensions of the stepped specimen are shown in Figure 1, together with the orientations of the 6 18Ni 200 Grade specimens with respect to rolling direction and plate thickness. The fabrication and validation processes are given in Appendices 1(a), (b) and (c) for 18Ni 200 Grade, PH13-8Mo, and A286 respectively. The fabrication and evaluation processes differ for the three materials in a number of respects, the most important of which is the position, if any, of heat-treatment and cryocycle stages. For example, no high temperature heat-treatments are specified for the A286. In the case of the 18Ni 200 Grade, four specimens were annealed prior to rough machining while two were not, and then all six specimens were aged prior to final machining. A similar attempt was also made with the PH13-8Mo samples to vary the heat-treatment and rough machining sequences. Finally, the cryogenic temperature cycles were carried out on the fully machined samples for 18 Ni 200 Grade and PH13-8Mo but between the .060 in step milling and grinding stages in A286. Although these differences exist, nevertheless some conclusions may still be drawn from the data.

There were also inconsistencies in the machining operations for the three different materials. In the case of the 18Ni 200 Grade, there is a difference in the length of the .060 in grinding stage, with specimens CLS and CLC having a 9 mm long step and LS, LC, TS and TC having a 6 mm step. These differences are summarized in Figure 2 for the five 18Ni 200 Grade, five PH13-8Mo and one A286 samples in our possession. The finish of the reference surfaces on many of the samples also show prominent coarse grinding patterns. As will become apparent in the next sections, many of the reference surfaces are NOT FLAT to the standard necessary to enable changes in the profile of the reference surface to be followed accurately. Finally, in the A286 and PH13-8Mo samples in particular, there are visible burn marks on the thinnest steps and in some cases the steps are not ground to a uniform thickness.

2.2 Validation

The major difference between the LaRC sourced specimens and that fabricated at Southampton (Soton 1) lies in the use of a contacting stylus system at LaRC and a contactless capacitance probe at Southampton. The use of a contacting stylus system has at least two major disadvantages: (a) the reference surface may get scratched if the stylus is dragged across it, and (b) the support system needs to be rigid enough to resist the stylus pressure.

The layout of the measuring fixture and the location of the support points are shown in Figure 3, together with the positions of the measuring stations A-X. Figure 3 is in fact a typical work sheet in which the deflections measured at positions A-X are tabulated on the left hand side of the work sheet. For the 18Ni 200 Grade samples, eight such work sheets would describe the progress of each specimen from rough machining to cryocycling.

As can be seen from Figure 3 the specimens are supported on two 5/8 in and one 3/16 in balls, arranged in a triangle, while specimen location is achieved by the three 1/4 in dowels. As we shall see from the results presented in the next sections, this arrangement does not seem to allow consistent and accurate relocation of the samples for revalidation between

fabrication stages and is thus one of the areas that will need rethinking before further work is carried out.

3. Choice of Format for Presentation of LaRC Results

As noted earlier, the verification procedures adopted by LaRC and their subcontractors produced 24 data points per specimen which gave the deflections at 24 pre-determined locations in the reference plane. As the eye is able to infer more about the shape and profile of a surface if that surface appears three-dimensional, it was decided to attempt to present the data in the form of pseudo-isometric surfaces. Reference to any of the data presentation figures will show that in each case the specimen is indicated with its steps facing downwards, and that a rectangular grid pattern is drawn on the reference surface. The dimensions of the specimen are shown on its front edge. Near its back edge, the intersections of the rectangular grid points, reading from left to right, represent the positions of the measurement stations A-H. Along the centre line, again from left to right, the grid intersections give the locations of stations I-P, while the intersections nearest the front give stations P-X.

A system of axes is shown set up perpendicular to the reference surface representing positive deflections ranging from .008 in above the reference plane to negative deflections .002 in below it. At each measuring station, A-X, the deflection measured by the appropriate validation stage is plotted as far above or below the plane as required by the scale of axes. As the deflections are plotted, adjacent points are joined by lines, broken or solid, to give an indication of the profile from the thick "leading edge" to the thin "trailing edge" of the stepped specimen. Three such profiles are drawn, using the deflection at stages A-H, I-P and P-X respectively. Finally, the three end points corresponding to stations H, P and X are joined together to give an impression of the curvature of the thin "trailing edge" of the specimen.

Thus, for each verification stage, the 24 readings obtained were used to create an impression of the three-dimensional shape of the reference surface at this stage of the fabrication sequence. For the 18Ni 200 Grade, there were 8 verification stages for each sample, while the PH13-8Mo and A286 had 7 and 6 stages respectively. For each separate sample, all stages are shown together on one sheet so that the reader can follow the progress through the various stages of fabrication. In most cases two different stages are shown on the same diagram, differentiated by line type and symbol, while in some cases 1 or 3 stages are shown per diagram for clarity or convenience. In all instances, the stages are labelled at the side of each diagram.

In order to present the data with the greatest clarity, and also to make the task of handling the large number of data points manageable, computer programs were written to plot out the results. A total of 2904 data points were measured on the 17 samples in this phase of the project.

The results show with adequate clarity the way in which the profile of the reference surface changes during the fabrication sequence. It is, however, necessary to exercise some care when trying to obtain more quantitative information about the deflections and their changes. In particular, it should be noted that the third support point of the verification fixture is located approximately at the center of the .060 in thick flat, and that when the samples are revalidated it is this point that is used to recreate the horizontal plane. If the reference surface is curved, as it is in many of the measuring stages, this will cause the points

BCD, JKL and RST to lie below the horizontal and the extreme points GH, OP and WX will show apparent deflections that are less than they should be. This point will be reconsidered later in Section 7.3.

Finally, although it has been possible to create representations of the profile of the reference flat with 24 data points, it is not possible to use the data to obtain quantitative estimates of the surface stresses present. Continuous traces from which radii of curvature can be measured are necessary if stresses are to be obtained using the method given in Reference 2.

4. Comments on the Surface Profiles derived from the Data on Vascomax 200

A total of 6 samples of 18Ni 200 Grade were fabricated and the surface profiles derived from the data procured by LaRC are shown on Figures 4 to 9. Figures 4 and 5 are for the control samples CLS and CLC that were NOT annealed prior to fabrication and they provide a suitable starting point from which to consider interpretation of the results.

In the top left quadrant of Figure 4 the surface as defined by the points taken during validation stage #4 is shown by the # symbols and the - - line and this represents its condition after rough milling, labelled #4 (slab mill). It can be seen that this surface is very well defined and flat with no point lying more than .0002 in away from the plane. The second series of points shown in this quadrant are marked with \$ symbols and joined with - . - . lines and represent the surface as it existed after the .236 in and .118 in steps had been machined using a flat bottomed end mill, as recorded during validation stage #6. The surface is depressed below the horizontal by up to about .001 in at the extreme right hand side with both the front and back profiles being slightly lower than the center. Moving on to the bottom left quadrant the surface defined by the = symbols and the - . . - . line type represents the situation at validation stage #8 after the 925F aging treatment had been carried out. Comparison with the results from stage #6 in the top left quadrant shows that there is very little dimensional change during the aging treatment, as is to be expected from such a stable material as 18Ni 200 Grade. The second surface in the bottom left quadrant defined by the * symbols and solid line is the reference surface created by grinding, and as a reference surface it is in fact quite good with only a few points lying up to .0002 in above or below the horizontal.

The end 24 mm (.944 in) of the specimen was then milled using a ball ended cutter down to a thickness of .075 in (1.875 mm). The resultant surface as validated in stage #12 is shown in the top right hand quadrant by the * symbols and - . . - . line type and it can be seen that the surface curves gently upwards to give an end deflection of between .002 and .003 in above the horizontal, with almost all of the deflection coming from the end three points on each linear profile. Subsequent grinding of the end 21 mm (.84 in) down to a thickness of .060 in (1.5 mm) produced the surface shown in the same quadrant by @ symbols and - . . - . lines, labelled #14 (>.060 GRIND). This surface is deflected slightly downwards showing that this grinding operation induced tensile stresses into the machined surface.

The final machining operation was to grind the end 12 mm (.472 in) long step down to a thickness of .030 in (.75 mm) and the resultant surface is shown in the bottom right hand quadrant by + symbols and lines, labelled #16 (>.030 GRIND). Comparison with the previous surface shows that the extreme end of the specimen has been depressed slightly further,

particularly at the back edge. The specimen was then cryocycled to liquid nitrogen temperature three times before being revalidated in #18, the results of which give the surface shown by the \$ symbols and dotted lines, labelled (CRYOCYCLE). Comparison between the two surfaces shown in the bottom right hand quadrant appears to show a small amount of movement caused by cryocycling, particularly on the back linear profile. Previous results at Southampton (Ref.2) had suggested that 18Ni 200 Grade did not distort during cryocycling so these deviations need to be treated with caution. In general, the standards of machining and validation on this sample, CLS, can be considered satisfactory. The behaviour of the other control specimen, CLC, is shown in Figure 5. The deflections caused by the .060 in milling stage and validated in #12 are somewhat larger than in CLS, and in consequence the thicker parts of the specimen slope below the horizontal from left to right because of the location of the 3rd support point, as discussed in sections 3 and 7.3. Comparison of the pre- and post-cryocycled surfaces appears again to show some small movement during cryocycling.

The remaining four specimens LS, LC, TS and TC shown in Figures 6 to 9 all received a two stage annealing treatment recommended by Vasco Pacific at 1850F and 1550F prior to rough machining, and it would appear from comparison with the unannealed control specimens that this heat treatment was NOT beneficial as all the annealed specimens show much greater deflections than the unannealed controls. However, there may also be other factors that have to be considered before this initial supposition can be proven.

In all 4 specimens, the surface produced by rough machining is tolerably flat but after milling the .236 in (6 mm) and .118 in (3 mm) steps, the two surface specimens show noticeably greater positive deflections, and thus compressive stresses, than do the center specimens. There is, however, little subsequent change in profile of the LS and TS samples when they are aged at 925F, whereas both of the center specimens seem to develop positive deflections as a result of the 925F aging treatment. The significance of these observations is, however, brought into question when the profiles generated from the #10 data are examined for all 4 specimens. Reference to the machining schedule for 18Ni 200 Grade in Appendix 1(a) will show that #9 reads as follows:

"#9 Surface grind and/or lap flat surface (bottom) to thickness using a maximum of .0005 in down-feed per cut. Surface finish to be 32 micro-inches. This surface will be used as a reference standard."

It is clear from the #10 surfaces shown in Figures 4.3 to 4.6 that they are definitely NOT of reference standard FLATNESS. The worst example can be found in the center profile of specimen TC, in which the recorded deflection is .0020 in above the horizontal for measurement station P, and when this is corrected for the downward slope of the whole surface, the true deflection is, in fact, nearer .0050 in. Contrast this with the reference surfaces produced on samples CLS and CLC in which no point lay more than .0002 in away from the horizontal and it is obvious that the 4 annealed samples behaved differently. Certainly they did not have a reference surface that was lapped flat.

The out of flatness of the reference surfaces should be borne in mind when the results of subsequent machining and validation stages are considered. Despite the effect of the poor reference flat, the significance

of the very large deflections created by the .060 in milling operation validated in #12 should not be overlooked as they are generally about 2-3 times those shown by either the unannealed control specimens CLS and CLC or the Sotor 1 sample. The set up of the specimens for validation also seems to be in error as may be seen from Table 1.

Table 1: Recorded Deflection for 18Ni 200 Grade Specimens at #12 Validation

Station	Deflection for Specimen (inches)			
	LS	LC	TS	TC
A	.0004	.0006	.0002	- .0015
I	.0018	.0006	.0006	- .0015
Q	.0016	.0005	.0012	- .0016

All of these deflections should read zero for a well set up specimen. If this basic requirement is not met, the value of subsequent measurements is significantly reduced.

In all four specimens the .060 in grinding operation caused some decrease in the residual compressive stresses induced by the previous milling steps, but in no case were they eliminated even after the second grinding operation that reduced the thickness of the end step to .030 in.

Examination of the surface profiles shown in the bottom right hand quadrant for the #16 and #18 validation stages shows that there is a reasonable consistency between the deflections measured before and after cryocycling for the stations at the thick ends of the specimens that define the basic profile of the surface. It is, therefore, possible to have some confidence in the validity of the deflections measured at the more active thin sections. In all four specimens there is in fact a very close agreement between these two profiles indicating that there was very little, if any, movement during cryocycling.

We have thus the somewhat paradoxical result that the generally well-behaved specimens CLS and CLC appear to show a greater degree of movement during cryocycling to liquid nitrogen temperature than is found in the poorer annealed samples. Given the criticisms made earlier about the poor quality of the reference surfaces and set up prior to validation, it is reasonable to conclude that 18Ni 200 Grade has a good stability during cryocycling.

5. Comments on the Surface Profiles derived from the Data on PH13-8Mo

There were 7 specimens of PH13-8Mo stainless steel investigated in this phase of the program and their machining and validation schedule was as shown in Appendix 1(b). There were only seven validation stages specified or carried out for this material and thus Figures 10 to 16 each show the seven surface profiles derived from the LaRC data. Two basically different machining and heat-treatment schedules were followed for these specimens:

for A-LS, A-LC, A-TS and A-TC, it was
 1) rough machine, 11) heat treat, 111) finish machine, 1v) cryocycle

for A-CLS, A-CLC and A-LSA, it was

i) heat treat, ii) rough machine, iii) finish machine, iv) cryocycle.

For sample A-LSA an additional cryocycle was in fact specified between rough machining and finish machining, but in the event it was omitted.

Thus, in effect, A-LSA received the same treatment as sample A-CLS, so that comparison between their two sets of results shown in Figures 10 and 11 respectively could give some idea of how consistent are the results from two supposedly similar specimens. As before, the first two profiles are shown in the top left quadrant. Set-up of the line AIQ is such that the measured deflection at Q is $-.0013$ in and thus below the horizontal while the back position A is $.0002$ in above it. In contrast the back right point H is $.0012$ in above the horizontal while the front right position X shows a deflection of $-.0005$ in.

Thus the whole specimen is set up on the tilt, and this tilt is evident in all of the subsequent surface profiles. Although it is not clear from the sketch of the mounting fixture that was shown in Figure 3, it would appear that it is not possible to alter the height of the two $5/8$ in balls relative to each other in order to align the top of the specimen to be accurately horizontal along the line AIQ. An alternative explanation for the observed misalignment might be that the top and bottom faces of the specimen were not parallel. Even allowing for a possible tilt in the specimen alignment, it is still not possible to account for the apparent shape of the reference surface created from the readings of validation stage #10.

The surfaces shown in the top right hand quadrant show that milling the $.060$ in step created compressive stresses and hence the positive deflections exhibited by #14, while subsequent grinding cancelled out these compressive stresses and replaced them with residual tensile stresses and thus the negative deflections found for the #16 validation stage. Furthermore, the magnitude of the change from compressive to tensile stresses is considerably larger than anything seen hitherto in 18Ni 200 Grade.

Finally, the picture is completed by the two profiles shown in the bottom right hand quadrant. The first six measurements taken at the thicker end of each linear profile are virtually co-incident for the #18 and #20 surfaces representing the pre- and post-cryocycling situations respectively. Thus the differences shown by the thinner sections can be believed as a genuine, and unfortunate, indication of the material's lack of stability on cryocycling into liquid nitrogen.

The picture presented by the similar sample A-CLS is no better. The #6 and #8 surfaces are tilted and the reference surface in #10 is not flat, having a pronounced upward deflection of both thin corners with respect to the center! The large compressive stresses induced by milling the $.060$ in step, #14, are partially lowered by subsequent grinding, #16, but in this case the tensile stresses induced are not large enough to offset them completely and there is a net residual compressive stress.

Finally, although the measurements taken on the thicker sections before and after cryocycling do not coincide, it can be seen that the post-cryocycle surface simply slopes down more sharply than before. Thus, the shift towards positive deflections shown by the thinner sections of the specimen are an underestimate of their true magnitude, thus confirming the instability of PH13-8Mo to cryocycling.

The third specimen heat-treated prior to rough machining was A-CLC and its results are given in Figure 12. This specimen appears slightly better behaved than the previous two in that it is not quite so tilted, nor is the reference surface so out-of-flat. The compressive stresses induced by milling the .060 in step are almost counterbalanced by the tensile stresses created during grinding to leave net compressive stresses except at the extreme tip.

The cryocycle results once again confirm that the material is not dimensionally stable. Figures 13 to 15 are for the four specimens that were rough machined prior to heat-treatment and generally their behaviour seems indistinguishable from those discussed earlier. All have tilting problems to a greater or lesser extent and the reference surfaces are not flat. The compressive stresses induced by milling are more or less compensated by subsequent grinding-induced tensile stresses. Most significant is the observation that in every case the deflections of the thinnest sections are more positive after cryocycling than before, thus fully confirming the dimensional instability of the material when cryocycled.

Taking an overview of all seven specimens, it would appear that the variation in order of the heat-treatment had little or no effect; there are indications that the deflections produced in samples cut from the surface may be slightly greater than those from the center but the trend is not conclusive. Neither is it possible to distinguish longitudinal and transverse effects.

6. Comments on the Surface Profiles derived from the Data on A286

A total of 4 samples of the precipitation hardened stainless steel, A286, were in this phase of the project and the surface profiles generated from the LaRC data are presented in Figures 17 to 20. The fabrication schedule is detailed in Appendix 1(c), from which it can be seen that for these specimens the reference surface was ground onto the rectangular slab to bring it down to size 2.362 x 2.362 x .472 in thick, rather than after machining the .236 in and .118 in steps as in the 18Ni 200 Grade and PH13-8Mo specimens. The reference surfaces are shown in the top left hand quadrant, identified by = symbols and - . - . lines. Generally these surfaces are of a reasonably good quality and they are set up quite well with just a slight tendency to tilt up a bit at the back right hand corner and down at the left.

The very striking effect shown in this quadrant is undoubtedly the very large deflections created in all four specimens by the process of milling the .236 in and .118 in steps, the true deflections being even larger than those indicated because of the left to right downward slope of the reference plane itself. As noted in other parts of this report it is not possible to calculate the magnitude of these compressive stresses because there are not enough data points to establish the circular arc. Very rough calculations indicate, however, that these surface stresses could be of the order of 10 Ksi.

Even larger deflections were created in all specimens by milling the .060 in step although they do not necessarily infer higher compressive stresses because the beam thickness has now been reduced. As noted above, the A286 specimens were cryocycled at this stage and the surfaces before and after the cryocycles are shown in the bottom left hand quadrant. The pre-cryocycle condition is shown by the @ symbols and - . - . lines and labelled #8A (>.060 mill), while the post-cryocycle condition has + symbols, dotted lines and is labelled #8C (>cryocycle). There is a very good

agreement between the two surfaces in all cases, thus confirming the known excellent cryogenic stability of A286 stainless steel.

The post-cryocycle surface is also plotted in the upper right hand quadrant to allow easy comparison with the surfaces produced by the .060 in grinding stage #10, * symbols and - . - . line type, and the following .030 in grind of the end section, shown by * symbols and continuous lines. The comparison between the surfaces created by milling the .060 in step and grinding the .030 in step, offers the most spectacular indications of work-induced dimensional changes, especially in the two center specimens LC and TC, where large positive deflections due to compressive stresses are overcome in the thinnest step by equally large grinding-induced tensile stresses.

The deflections induced in the two surface specimens by milling are somewhat smaller than in the center specimens, neither do the subsequent grinding stages seem to cause such large tensile stresses. These trends are probably significant but it would need further confirmatory tests if it were thought to be an important enough aspect of the behaviour of this material.

7. Additional Information on the Surface Finish and Profile of Selected Samples

7.1 Surface Finish

In view of the comments made earlier about the apparently poor finish on the reference surfaces, the surface finish of three samples, 18Ni 200LC, A286LS, and PH13-8Mo, together with that of the 18Ni 200 Grade sample, Soton 1, were recorded using a contacting stylus probe, a Talysurf made by Rank Taylor Hobson. The location and orientation of the traces measured on all four samples is as shown in Figure 21(a). Trace A is taken across the width of the specimen at its thickest point and is thus indicative of both the surface finish and the flatness along this line, which remains essentially unchanged throughout all the fabrication sequences. Trace C is also taken across the width of the specimen, but in this case it is at its thinnest point near the "trailing edge". If the surface finish were uniform over the reference surface, the measured surface finish for trace C would be the same as that for A. As, however, the later stages of machining cause the thin trailing edge to bow, the trace recorded shows the surface finish superimposed on the bowed profile.

Trace B is taken along the length of the specimen from thickest to thinnest sections, but, due to the limited deflection capability of the Talysurf of about .001 in at this sensitivity, it is not possible to measure to the thinnest end of most specimens as their deflections exceed .001 in. Nevertheless, comparison of the initial, linear portion of trace B with either traces A or C shows whether there is any pronounced anisotropy in the machining and surface finish on the reference surface.

Figure 21(b) shows the trace obtained during calibration for a known step height of .0001 in (100 microinches). This sensitivity setting was used for all the traces shown in Figures 21, 22, 23 and 24.

Figure 21(c) shows the trace along line A for sample Soton 1. A similar surface finish is also exhibited in traces C and B. Now that our experience with a total of eighteen samples has shown that deflections produced during step fabrication are typically in the range .001 to .010 in, it is clearly unnecessary to specify such high surface finishes for subsequent specimens.

Traces C and B in Figures 21(d) and 21(e) give an indication of the profile changes produced during fabrication. As, however, they only show those portions for which the total deflection varies by less than .001 in, they should not be used for considering profile changes.

Reference to Figure 22 shows the three comparable traces obtained when the Vascomax 200 sample LC was measured at Southampton. Traces A and C in Figures 22(c) and 22(d) show that no peaks lie further than .00005 in, 50 microinches, away from the mean line, while in Figure 22(e), trace B shows an even better surface finish in the longitudinal direction with peaks lying within about 20 microinches from the mean. In relation to the deflections produced during fabrication, and the inconsistencies apparent in the validation procedure, this surface finish is perfectly acceptable.

The traces obtained for the A286 specimen LS shown in Figure 23 show a poorer surface finish than that produced on the 18Ni 200 Grade samples. In particular, trace A in Figure 23(c) shows deviations from the mean of about +80 microinches occurring in a regular wave-like pattern. On the other hand, trace C in Figure 23(d) is smoother, although it is superimposed on a large transverse bowing of this thin section. Trace B in Figure 23(e) shows that deviations in the longitudinal direction are about 20-30 microinches away from the mean line. There appears, therefore to be a strong anisotropy in the surface finish on this sample.

Finally, Figure 24 shows the results obtained for the PH13-8Mo sample A-TS. Compared with any of the previous samples, the surface finish has a much shorter wavelength with deviations less than +40 microinches from the mean, except for occasional spikes visible in traces B and C which are about 100-150 microinches above the mean line. Very similar finishes are shown in traces A and C for the transverse directions, while the longitudinal trace B shown in Figure 24(e) shows a longer wavelength component in the surface finish.

Nevertheless, with the possible exception of trace A shown in Figure 23(c) for A286 which is on the upper limits of what might be considered as acceptable, the surface finish of all the specimens can be considered to be satisfactory for use in the stepped specimen program. As long as no deviations are in excess of +50 microinches from the mean line, errors due to surface finish will be less than .0001 in, which is a much lower figure than the errors introduced by other sources.

7.2 Profile

In order to be able to compare the profiles generated from the data obtained in this phase of the stepped specimen project, and that obtained from the 18Ni 200 Grade sample, Soton 1, the three samples, 18Ni 200 LC, A286LS and PH13-8Mo A-TS, were revalidated at Southampton using the contactless capacitance probe method described in Reference 2. As the area "seen" by the capacitance probe is about 9mm^2 , small surface irregularities are averaged out and thus a good surface finish is not essential. 18Ni 200 Grade sample Soton 1 was also revalidated and Figure 25 shows the location and orientation of the 6 traces measured. Trace 3 was positioned so as to correspond to the line of the measurement stations A-H in the LaRC specimens, while trace 2 corresponded to stations I-Q and trace 1 to stations P-X. Traces 4, 5 and 6 are perpendicular to traces 1, 2 and 3 and trace 4 corresponds approximately to the line AIQ and trace 6 to the line HPX, while trace 5 lies between the lines BJR and CKS.

The black circles marked on the traces shown in Figures 25 to 32 correspond to the locations of the three points used to level the samples prior to validation. Also marked on each of these figures is the scale of the deflection, and on the longitudinal traces in Figures 25, 27, 29 and 31 the location of the steps in the specimen is also indicated.

The longitudinal traces recorded on 18Ni 200 Grade sample Soton 1, are shown in Figure 25. All three traces show clearly a sharp change at the position of the 3 to 1.5 mm step from a linear trace at the thick end of the sample to an almost linear trace at the thinner end. The maximum deflections of the extreme tips are .0030 in, .0032 in and .0023 in for traces 1, 2 and 3 respectively. Turning now to Figure 26, it can be seen that there is no variation across the width of the specimen along lines 4 and 5, but that trace 6 shows the edges to bow down compared with the centre by about .0003 in at the left and .0012 in at the right.

The corresponding traces for 18Ni 200 Grade sample LC are shown in Figures 27 and 28 for the longitudinal and transverse traces respectively. In Figure 27, the profile of the reference surface generated from the LaRC data is also shown inset at the top left of the figure and it can be seen that agreement is qualitatively very good. The nature of the longitudinal traces on this 18Ni 200 Grade sample differs significantly from that of Soton 1 in that there is no sharp change of slope between linear segments as in Figure 25, but rather a gradual upward deflection which starts between the 6 to 3 mm step and the beginning of the 3 to 1.5 mm change. As noted earlier, the fabrication sequence differed between the Southampton and LaRC specimens in that the LaRC samples have a smooth, curved change in thickness from 3 to 1.5 mm rather than a sharp step as in the Southampton specimen. It is possible that the smooth curves shown by traces 1, 2 and 3 in Figure 27 are in part due to this gradual change of section.

The quantitative aspects of these deflections will be considered in more detail in Section 7.3, but it is worth noting at this stage that the maximum deflections shown at the thinnest end of Soton 1 are .0030, .0032 and .0023 inches for curves 1, 2 and 3 respectively, whereas for sample LC the corresponding values are .0088, .0096 and .0086 inches respectively. It would appear, therefore, that 18Ni 200 Grade sample LC has a residual deflection three times larger than that of the Soton 1 sample.

Figure 28 shows the three transverse traces, 4, 5 and 6, recorded for sample LC. Traces 4 and 5 confirm the transverse flatness of this sample in the thicker sections, while trace 6 shows the now familiar transverse bowing. The magnitude of this center to edge bowing is about .0012 inches, which correlates reasonably well with the differences between curves 2 and 3 or 2 and 1 in Figure 27. The values shown in Figure 28 are the more reliable, however, because they are the results of direct measurements rather than by graphical construction.

Figures 29 and 30 illustrate the traces recorded on the PH13-8Mo sample A-TS. The longitudinal traces of Figure 29 resemble the previous set of traces for 18Ni 200LC in that they show a gradually increasing upward sweep with no abrupt changes which starts between the 6 to 3 mm step and the beginning of the 3 to 1.5 mm curved thickness change. As before, the reference surface generated from the LaRC data is also shown inset at the top left hand corner of the figure and it can be seen that agreement is qualitatively good. Figure 30 shows the corresponding transverse records and close inspection of traces 4 and 5 suggests that the edges are approximately .0002 in higher than the center in trace 4 and .0003 in higher in trace 5. The variations shown by trace 6 are larger and of such a form

that the center and both edges are at about the same level, with a dip of about .0008 in to the left and one of .0005 in in depth to the right of center.

The final set of traces shown in Figures 31 and 32 are for sample LS of A286 stainless steel. The longitudinal traces of Figure 31 are strikingly different from those for 18Ni 200 Grade and PH13-8Mo in that there is a reversal of the slope of the curves, and thus a change from residual compressive to tensile stresses, in the 0.75 mm thick end step. Furthermore, the curvature of the trace in the region corresponding to the end step of thickness 0.75 mm (.030 in) is a very good approximation to an arc of a circle as indicated by the circular arc superimposed on trace 2 in Figure 31. As noted in Reference 2, the skin stress in such cases is given by

$$F = E t a/c^2$$

where E is the elastic modulus, t the beam thickness, 2c the chord length and a the central deflection.

From Figure 31, using the appropriate scaling factors for the horizontal and vertical dimensions, we find that for a chord length, 2c of 0.4 in, the central deflection, a, is .001 in. The modulus of A286 is 29×10^6 psi and the beam thickness .030 in. Hence, on substitution:

$$F = \frac{2.9 \times 10^7}{2 \times 10^{-1}} \times \frac{3 \times 10^2}{2 \times 10^{-1}} \times \frac{1 \times 10^3}{2 \times 10^{-1}} \text{ psi} = 2.16 \times 10^4 \text{ psi} = 22 \text{ Ksi}$$

Thus the residual tensile skin stress left by the final grinding stage in the thinnest end step is of the order of 22 Ksi. For comparison, the compressive stresses induced in the 18Ni 200 Grade sample Soton 1 built up from 5 to 9 Ksi over the four end milling stages. Although a more thorough program of work would be necessary to confirm and understand these stress patterns in greater depth, these results are a further indication of the potential value of the stepped specimen program.

Inset in the top left corner of Figure 31 are the reference surfaces generated from the LaRC data for the #12 data points which were taken after the final .030 in grinding stage, and are thus directly comparable with the traces shown in the figure, together with that for the #8C data points taken after cryocycling. Two sets of surfaces are shown to clarify the position of the reference surface in the thicker parts of the specimen as the data is rather suspect for point R on the #12 trace. Comparison between the surface generated from the #12 LaRC data points and traces 1, 2 and 3 made at Southampton is qualitatively quite good despite the small number of points available in the LaRC data to define the profile of the thin end section.

Finally, Figure 32 shows the three traces 4, 5 and 6 taken in the transverse direction. As expected, trace 4 is essentially linear, while trace 5 shows a slight downward deflection at the right hand end and trace 6 reveals the familiar bowing of the thin end with, in this case, the greatest deflection of about .002 inches at the left.

7.3 Determination of the True Magnitude of the Deflections at the Thin Ends of the Stepped Specimens

As noted in Section 3, the method of support use in the validation stages is such that the third support point lies approximately beneath

measurement station M as shown in Figure 3. In most specimens the curvature starts somewhere to the left of this support point and thus the reference surface seems to slope downwards from left to right. Many of the negative readings shown in the validation stages are therefore due to this downward slope of the whole reference plane, rather than being indications of true negative deflections from the reference plane. Furthermore, the recorded magnitudes of the positive deflections from the measurement stations at the thin end of the specimen are considerably lower than the actual deflections.

These effects are demonstrated in Figure 33 for the 18N1 200 LC and PH13-8Mo A-TS samples. The data points at measurement stations A-H are plotted using X--X symbols, those at stations I-P using \odot — \odot symbols and those at Q-X using .---. . Straight lines are drawn to be best fits through the first three data points for each profile and then projected to extend beneath the points measured at the extreme stations, H, P and X. The true deflection is then obtained from the vertical distance between the projected line and the measurement point. For 18N1 200 Grade sample LC these gave true deflections of .0070, .0086 and .0077 inches for positions H, P and X, while reference to the Southampton measurements shown in Figure 27 gives deflections of .0082, .0092 and .0084 inches respectively. Considering the uncertainties involved in drawing the best fit lines, and the fact that the Southampton traces were taken over 6 months after the LaRC readings on samples that had not been boxed or handled with any particular care, agreement is very satisfactory.

A similar series of constructions is shown in the lower part of Figure 33 for the PH13-8Mo sample A-TS. These give deflections of .0094 for position H, .0107 for P and .0092 inches for X respectively, while the corresponding values taken from Figure 29 are .0085 from trace 3, .0096 from trace 2 and .0090 inches from trace 1. Once again, therefore, agreement between the two sets of measurements is very good.

Data from the A286 sample LS is more difficult to handle because it is difficult to get a good linear fit to the first three points on the linear profiles and this introduces a large uncertainty into the position of the extrapolated value at the thin end of the sample. Nevertheless, as noted earlier, qualitative agreement between the two sets of measurements is good.

8. Conclusions

The main points that emerge from the data obtained from the specimens procured by LaRC, together with that obtained subsequently at Southampton, are summarized in Table 2. Although it has been possible to criticize a number of aspects of the machining and validating procedures, a large amount of useful information has nevertheless been generated by this phase of the stepped specimen program.

1. Of particular relevance is the poor dimensional stability shown by all the PH13-8Mo samples when cryocycled to liquid nitrogen temperature. This raises doubts as to the suitability of this material for use in models for cryogenic wind tunnels, particularly those applications such as an instrumented wing that would require a lot of fabrication.

2. Also of significance is the apparently poorer behaviour of the 4 18Ni 200 Grade specimens that were annealed prior to rough machining. If these results are genuine, it suggested that this type of heat-treatment should not be used.

3. There do not seem to be any significant differences between the behaviour of specimens orientated parallel and perpendicularly to the major rolling axis of the plate. However, metallographic examination suggests that none of the three materials tested had strongly orientated textures, so these results do not rule out orientation effects in the more highly textured materials. Although there are indications that there are some differences between center and surface specimens, the trends are not very strong and are contradictory inasmuch as the surface specimens seemed to be more active in the 18Ni 200 Grade, while the opposite trend was indicated in the A286.

4. Despite first appearances, the surface finish does not appear to be critical, as variations of less than +50 microinches only cause errors of .0001 inch which is at the lower limit for reliable measurements, particularly with stylus probes.

5. It is, however, vitally important that the reference surface be established as truly flat to within .0001 inch if subsequent changes are to be followed meaningfully.

6. It is equally vital that the samples can be set up with their reference surface in a truly horizontal plane. To this end, some thought should be given to alternative methods of support, particularly moving the 3rd point to beneath the thicker parts of the specimen which do not deflect when the thinner parts do so. In this way, changes in the shape of the reference surface can be followed more easily and more accurately.

9. Recommendations

1. A similar configuration of stepped specimen be used for the next three samples, A286, PH13-8Mo, and 18Ni 200T.
2. All three samples should have the same fabrication and validation sequence, which should take into account the lessons to be learned from this phase of work.
3. Some of the specimens left over from this phase of the program should be used for additional tests, such as further thermal cycling or high-temperature stress-relieving heat-treatments.
4. In the near future a more closely controlled series of tests should be carried out on one particular material, possibly the new 18Ni 200T, in order to obtain a deeper understanding of the stress levels created by different machining techniques and how they may be controlled by thermal stress relief.
5. Some thought be given to the optimum form in which the data is to be presented so that the possibility of computer controlled data storage, analysis and presentation can be investigated.

References

1. Wigley, D.A. "The Problem of Dimensional Instability in Airfoil Models for Cryogenic Wind Tunnels." NASA High Number Contractor Report No. CR 166003. Presented at the Cryogenic Models Workshop, NASA Langley Research Center, Virginia, May 5th-6th 1982.
2. Wigley, D.A. "A Proposed Configuration for a Stepped Specimen to be used in the Systematic Evaluation of Factors Influencing Warpage." NASA CR-166004, August 1982.

APPENDIX 1 (a)

April 20, 1982
Amended May 3, 1982

FABRICATION PROCESS FOR 18N1 200 GRADE

STABILITY STEP SPECIMENS

1. Specimens LS, LC, TS, and TC to be heat-treated as follows:
 - a. Anneal at 1840°F - 1870°F for forty-five (45) minutes to one (1) hour. DO NOT EXCEED 1870°F.
Air cool to room temperature.
 - b. Complete annealing process by heating to 1550°F $\pm 20^\circ\text{F}$ and hold for forty-five (45) minutes to one (1) hour. Air cool to room temperature.
 - c. Q. C. to verify compliance of heat-treating procedure as per Steps 1a and 1b.

Control specimens CLS and CLC will not receive this heat-treatment.
2. Rough machine all specimens to size 2.362" x 2.362" x .482" thick using a new flat bottom end mill. (Flood cool using Cambelene Blue-Cool)
3. Mark end of specimens as indicated on drawing.
4. Map, measure, and record as per special instructions.
5. Machine the .236" and the .118" steps to +.010" to leave the .118" step 1.417" long using a flat bottom end mill. (Flood cool using Cambelene Blue-Cool)
6. Map, measure, and record as per special instructions.
7. All specimens to be aged at 900°F to 925°F for six (6) hours.
Air cool to room temperature. Q. C. to verify compliance of heat-treating procedure.

FABRICATION PROCESS FOR 18N1 200 GRADE

STABILITY STEP SPECIMENS

(continued)

8. Map, measure, and record as per special instructions. Also map and record hardness check.
9. Surface grind and/or lap flat surface (bottom) to thickness using a maximum of .0005" down-feed per cut. Surface finish to be 32 micro-inches. This surface will be used as a reference standard.
10. Map, measure, and record as per special instructions.
11. Machine the .060" step to a plus .015", .944" long. using a New ½" diameter ball end mill. Step-over (machine feed) to be .050". (Flood cool using Cambelene Blue-Cool)
12. Map, measure, and record as per special instructions. Also map and record hardness check.
13. Grind the .060" step to finish dimension, .709" long, using a maximum of .0005" down feed per cut. Surface finish to be 32 micro-inches. (Flood cool using Cambelene Blue-Cool)
14. Map, measure, and record as per special instructions.
15. Grind the .030" step to finish dimension, .472" long, using a maximum of .0005" down feed per cut. Surface finish to be 32 micro-inches. (Flood cool using Cambelene Blue-Cool)
16. Map, measure, and record as per special instructions. Also map and record hardness check.
17. Thermally cycle specimens in cryostat as follows:
 - a. Attach two (2) thermocouples to specimen for monitoring temperature.

FABRICATION PROCESS FOR 18N1 200 GRADE

STABILITY STEP SPECIMENS

(Concluded)

- b. Immerse specimen in liquid nitrogen until temperature of specimen reaches -320°F .
 - c. Remove specimen from cryostat and allow sufficient time for specimen to reach temperature.
 - d. Thermal cycle specimen three (3) times repeating steps 17a, 17b, and 17c.
18. Map, measure, and record as per special instructions. Also map and record hardness check.

Special Instructions - Prior to heat treatment, all surfaces must be finished to a 40 rms minimum. No tool marks. All inside corners shall have a .030" minimum radius.

APPENDIX 1 (b)

May 10, 1982

FABRICATION PROCESS FOR 13-8 SS
STABILITY STEP SPECIMENS

1. Material confirmation.
2. Rough machine specimens A-LS, A-LC, A-TS, and A-TC to $+.050''$.
3. Heat-treat all specimens as follows:
 - a. Solution treat at $1700^{\circ}\text{F.} \pm 15^{\circ}\text{F.}$ for $\frac{1}{2}$ hour.
 - b. Air cool to below 60°F. (cold water) hold temperature below 60°F. one (1) hour.
 - c. Age at 1400°F. for two (2) hours.
 - d. Air cool to room temperature.
 - e. Re-age at 1150°F. for four (4) hours.
 - f. Air cool to room temperature.
4. Machine all specimens to size $2.362'' \times 2.362'' \times .482''$ thick using a new flat bottom end mill. (Flood cool using Cambelene Blue-Cool)
5. Mark end of specimens as indicated on drawing.
6. Map, measure, and record as per special instructions. Also map and record hardness check.
7. Machine the $.236''$ and the $.118''$ steps to $+.010''$ to leave the $.118''$ step $1.417''$ long using a flat bottom end mill. (Flood cool using Cambelene Blue-Cool)
8. Repeat step 6.

FABRICATION PROCESS FOR 13-8 SS
STABILITY STEP SPECIMENS
(continued)

9. Surface grind and/or flat surface (bottom) to thickness using a maximum of .0005" down-feed per cut. Surface finish to be 32 micro-inches. (Flood cool using Cambelene Blue-Cool) This surface will be used as a reference standard.
10. Repeat step 6. Hardness check omitted.
11. Specimen A-LSA to be thermally cycled in cryostat as follows:
 - a. Attach two (2) thermocouples to specimen for monitoring temperature.
 - b. Immerse specimen in liquid nitrogen until temperature reaches -320°F .
 - c. Remove specimen from cryostat and allow sufficient time for specimen to reach room temperature.
12. Repeat step 6 on specimen A-LSA - This step omitted.
13. Machine the .060" step to a plus .015", .944" long using a new $\frac{1}{2}$ " diameter ball end mill. Step-over (machine cross-feed) to be .050". (Flood cool using Cambelene Blue-Cool)
14. Repeat step 6.
15. Grind the .060" step to finish dimension, .709" long, using a maximum of .0005" down-feed per cut. Surface finish to be 32 micro-inches. (Flood cool using Cambelene Blue-Cool)
16. Repeat step 6.
17. Grind the .030" step to finish dimension, .472" long, using a maximum of .0005" down-feed per cut. Surface finish to be 32 micro-inches. (Flood cool using Cambelene Blue-Cool)

FABRICATION PROCESS FOR 13-8 SS
STABILITY STEP SPECIMENS
(concluded)

18. Repeat step 6.
19. Thermally cycle all specimens in cryostat as follows:
 - a. Attach two (2) thermocouples to specimen monitoring temperature.
 - b. Immerse specimen in liquid nitrogen until temperature reaches -320°F .
 - c. Remove specimen from cryostat and allow specimen to reach room temperature.
 - d. Thermal cycle specimen three (3) times, repeating steps 19a, 19b, and 19c.
20. Map, measure, and record as per special instructions.
Also map and record hardness check.

May 4, 1982

FABRICATION PROCESS FOR A-286 STAINLESS
STEEL STABILITY SPECIMENS

1. Rough machine all specimens to size 2.372" x 2.372" x .482" thick using a new flat bottom end mill (Flood cool using Cambelene Blue-Cool).
2. Grind all specimens to size 2.362" x 2.362" x .472" thick using a maximum of .0005" down-feed per cut. Surface finish to be 32 micro-inches.
3. Mark end of specimens as indicated on drawing.
4. Map, measure, and record as per special instructions.
5. Machine the .236" and the .118" steps to +.010" to leave the .118 step 1.417" long using a new 1/2" diameter ball end mill. (Flood cool using Cambelene Blue-Cool).
6. Repeat step 4.
7. Machine the .060" step to a plus .015", .944" long, using a new 1/2" diameter ball end mill. Step-over (machine feed) to be .050" (Flood cool using Cambelene Blue-Cool).
8. Repeat step 4; cryo cycle (NASA); repeat step 4.
9. Grind the .060" step to finish dimension, .709" long, using a maximum of .0005" down-feed per cut. Surface finish to be 32 micro-inches. (Flood cool using Cambelene Blue-Cool).
10. Repeat step 4.
11. Grind the .030" step to finish dimension, .472" long, using a maximum of .0005" down-feed per cut. Surface finish to be 32 micro-inches. (Flood cool using Cambelene Blue Cool).

FABRICATION PROCESS FOR A-286 STAINLESS
STEEL STABILITY SPECIMENS
(concluded)

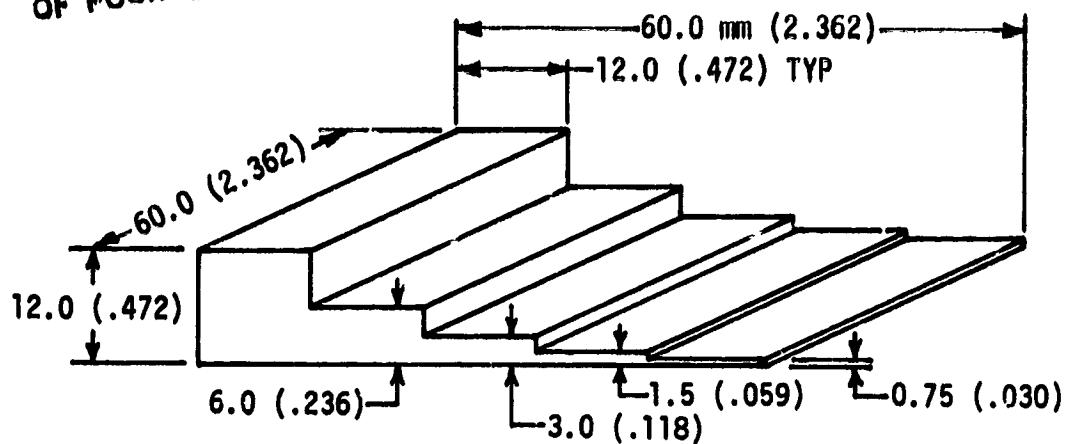
12. Repeat step 4.

SPECIAL INSTRUCTIONS: All inside corners shall have a .030" minimum radius. Cutwell 40 oil may be used if needed to produce a better finish. Mark each specimen with material identification A-286.

Table 2: Summary of Results from Stepped Specimens procured by LARC

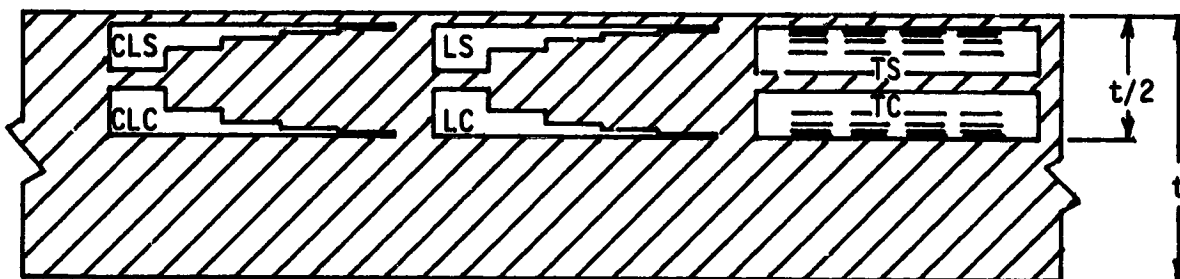
Characteristic	18N1 200 Grade	A286	PH13-8Mo
a) Cryogenic stability	Good.	Excellent.	Poor.
b) Flatness of ref. surface	CLC and CLS - good. LS, LC, TC, TS - bad.	All good.	All bad, A-LSA, A-CLS, A-TC worst
c) Surface finish of ref. surface	Variable, e.g. LS, TC show fine grinding marks, while TS and CLS also show coarser pitch. Talysurf show approx. 50µin finish.	Coarse grinding marks on TS and burn marks on thinnest section. Talysurf traces show waviness with amplitude $> \pm 50 \mu\text{in}$. 30 µin finish.	Medium pitch grinding marks visible on all specimens but Talysurf trace suggests approx
d) Set up for verification, out of true of line AIQ	CLC and CLS good LS, LC, TS and TC very poor especially at #10, #12 and #14, vary by $\sim \pm .001 \text{ in}$.	All reasonable to good with variations less than .0005 in.	Generally poor, with some points very bad, up to .002 in off line.
e) Fabrication and heat-treatment sequence	Pre-machining 2 stage anneal NOT beneficial All samples show good dimensional stability after 925F aging treatment.	Not applicable.	No apparently significant differences between samples heat-treated before or after rough machining.
f) Sensitivity to rough machining	CLC, CLS, LC and TC, almost unaffected. LS and TS show mild compressive stresses.	Deflections over .005 in created in LS, TS and TC by milling coarse steps.	Most specimens unaffected, small tensile stresses in A-LC, small compressive in A-LS.
g) Magnitude of deflection change from .060 mill to .030 grind.	Average of .003 to .005 in. No strong trends.	Varies from .008 for TC and TS to $\sim .016$ to .020 in for LS and LC.	Average of .005 to .008 in No strong trends
h) Differences between Surface and Center, Longitudinal and Transverse	Marginally larger deflections from step milling of Surface specimens LS and TS than Center. No significant difference between longitudinal and transverse	Slightly larger deflections shown by Center specimens than Surface.	Marginally more deflection from Surface than Center

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SPECIMEN CONFIGURATION

STAMP ENDS AS SHOWN



NOTES:

1. Specimens LS, LC, TS, & TC to be annealed before rough machining. Tempered after rough machining.
2. CLS & CLC are to be tempered after rough machining.
3. All specimens are to be measured after rough machining before and after each heat treatment.

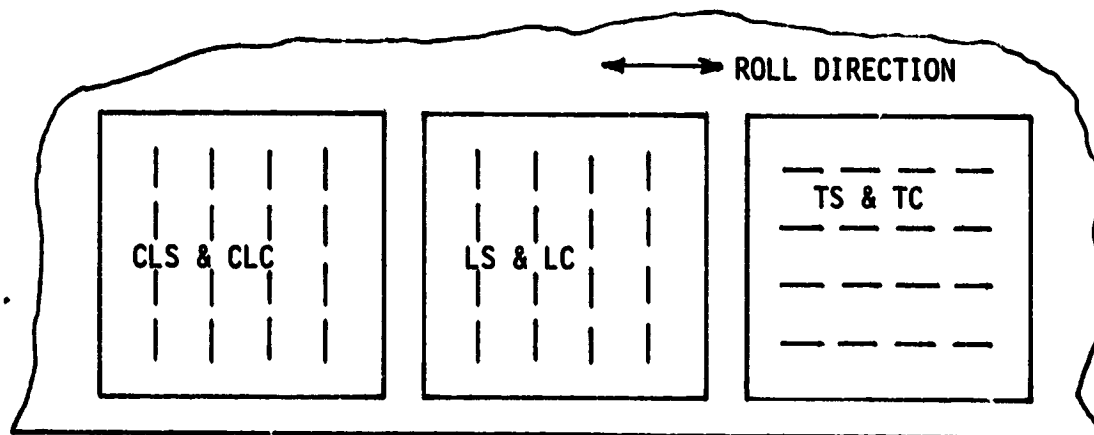


FIGURE 1. STEPPED DIMENSIONAL STABILITY SPECIMENS

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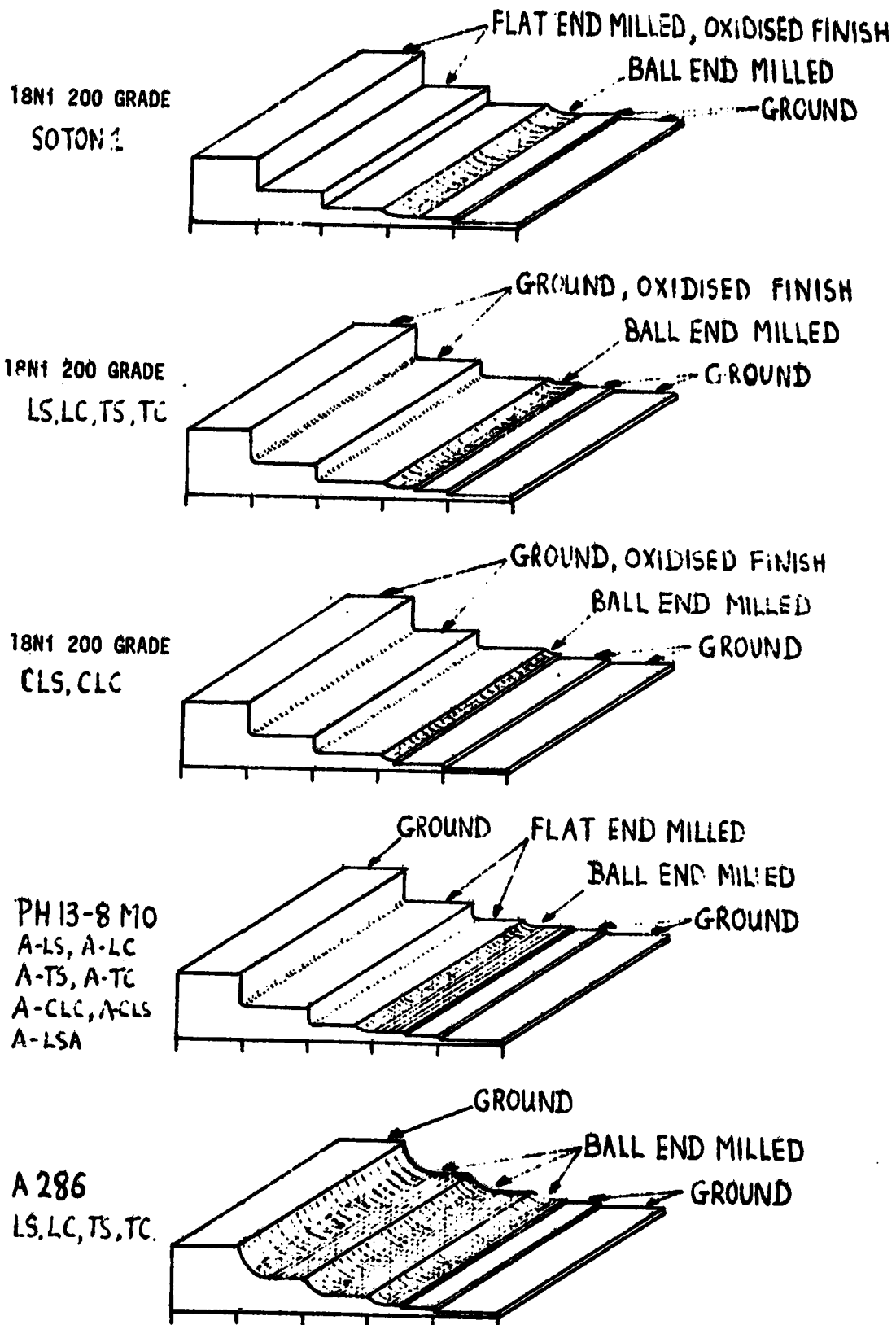


FIGURE 2. VARIATIONS IN MACHINING METHOD USED FOR STEPPED SPECIMENS

A	.0000
B	.0000
C	+.0001
D	+.0002
E	+.0002
F	+.0003
G	-.0003
H	-.0010
I	-.0001
J	-.0001
K	-.0001
L	-.0001
M	.0000
N	+.0001
O	-.0002
P	-.0004
Q	-.0002
R	-.0002
S	-.0002
T	-.0002
U	-.0002
V	-.0003
W	-.0006
X	-.0013
Y	
Z	

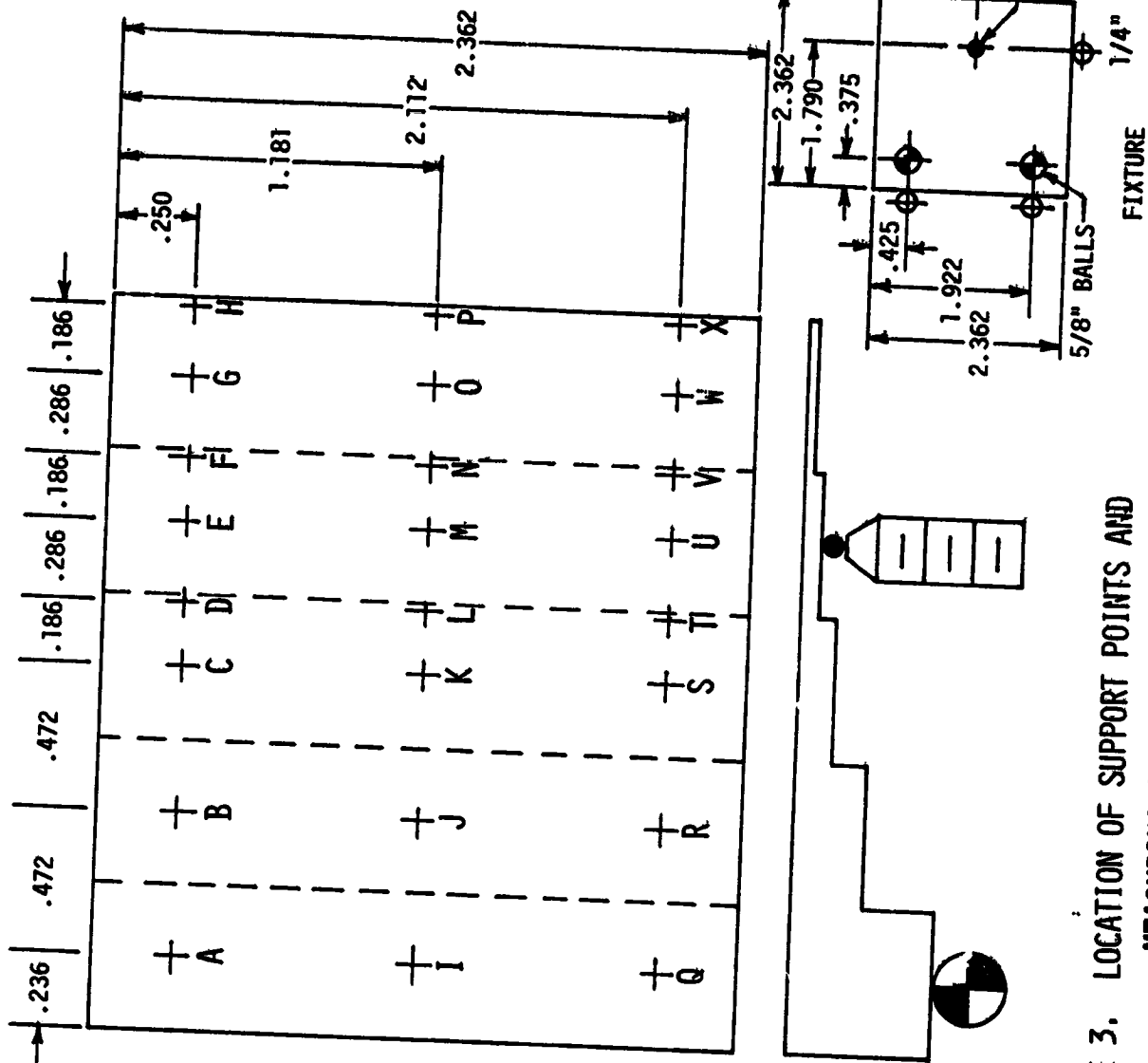


FIGURE 3. LOCATION OF SUPPORT POINTS AND MEASURING STATIONS

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OVERVIEW
QUESTIONS

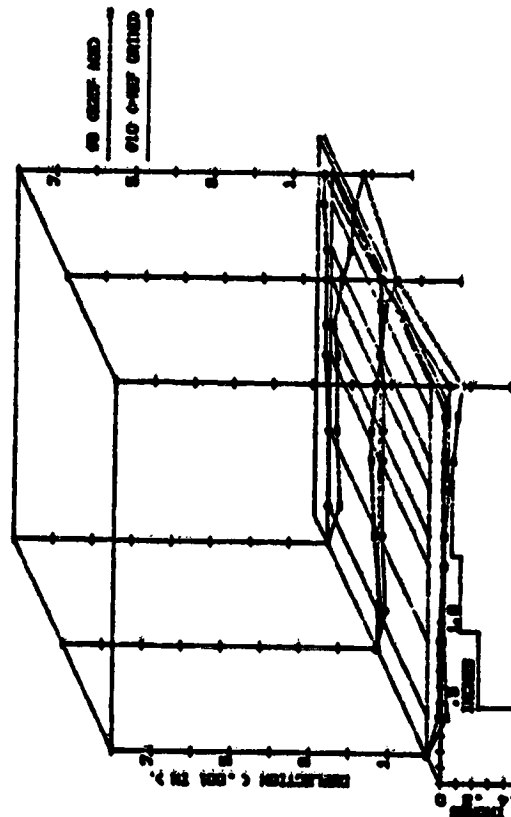
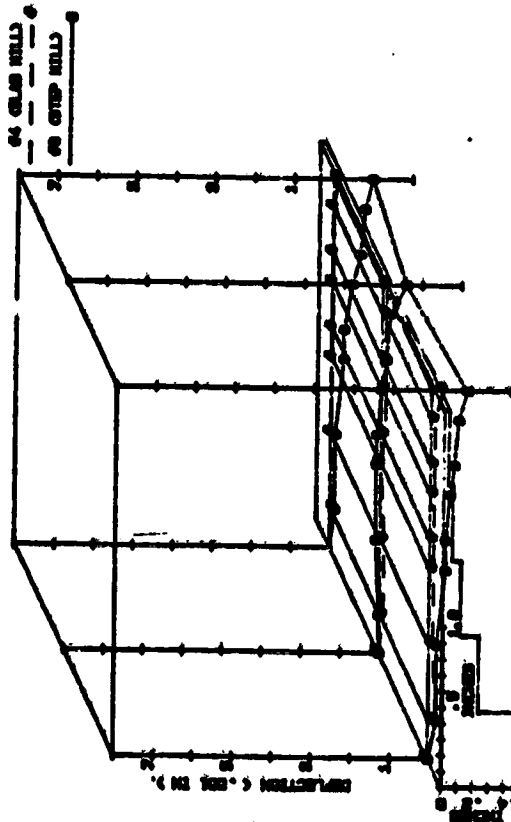
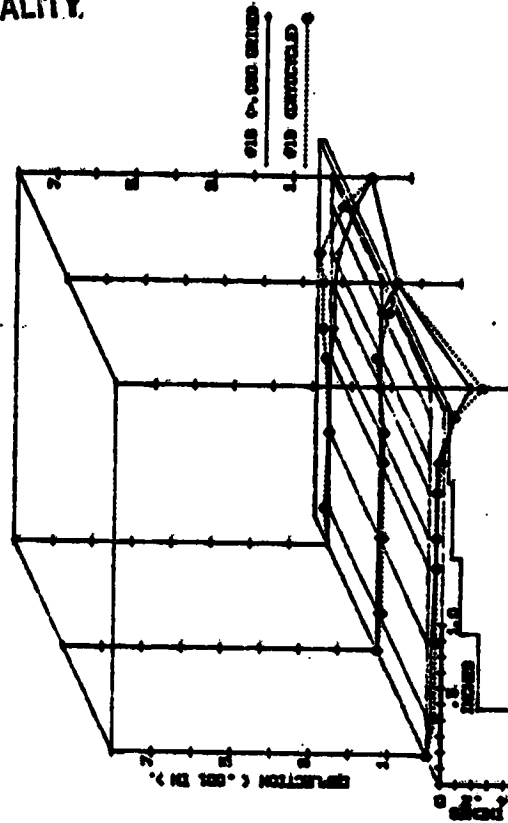
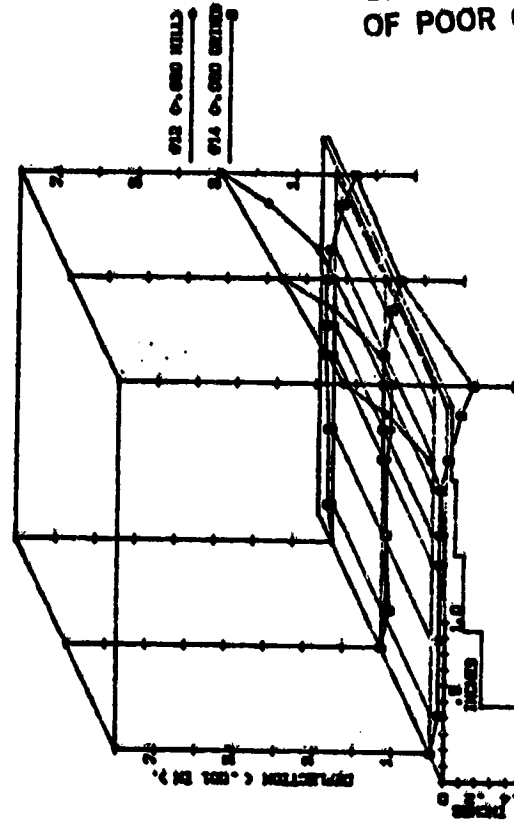


FIGURE 4. MATERIAL 18N: 200 GRADE SPECIMEN CLS (CONTROL, LONGITUDINAL, SURFACE)

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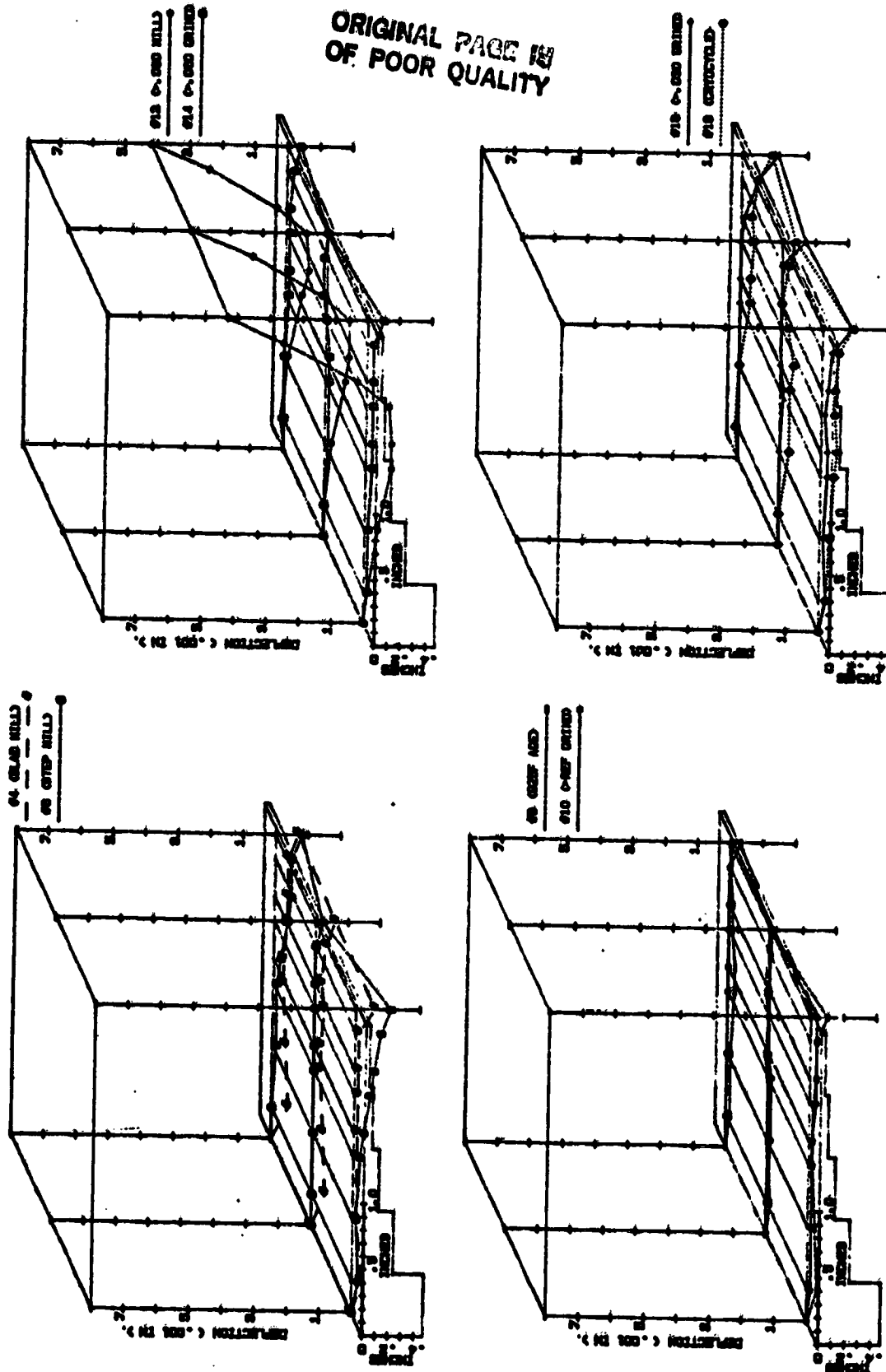


FIGURE 5. MATERIAL 18N1 200 GRADE SPECIMEN CLC (CONTROL, LONGITUDINAL, CENTER)

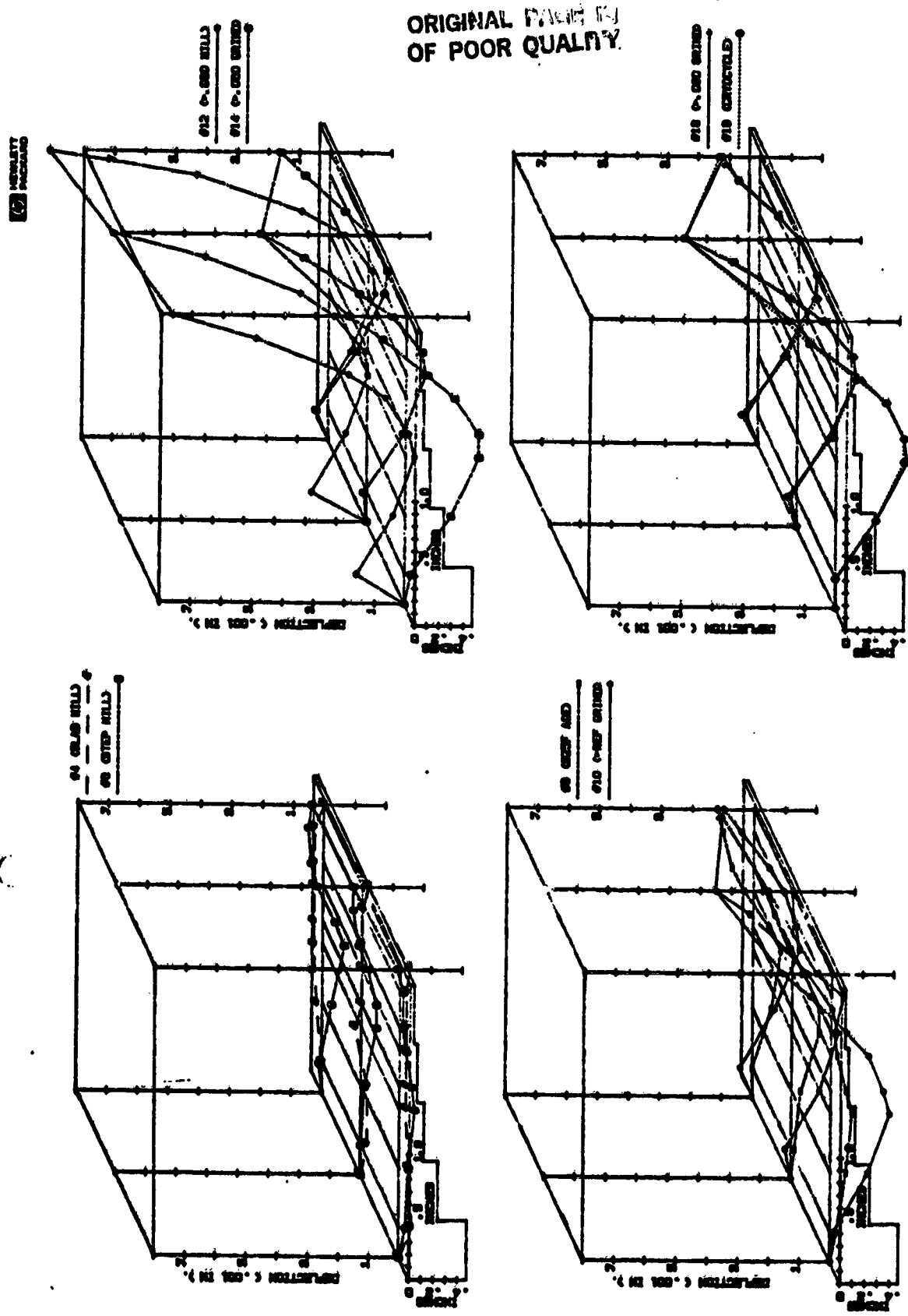


FIGURE 6. MATERIAL 18N: 200 GRADE SPECIMEN LS (LONGITUDINAL, SURFACE)

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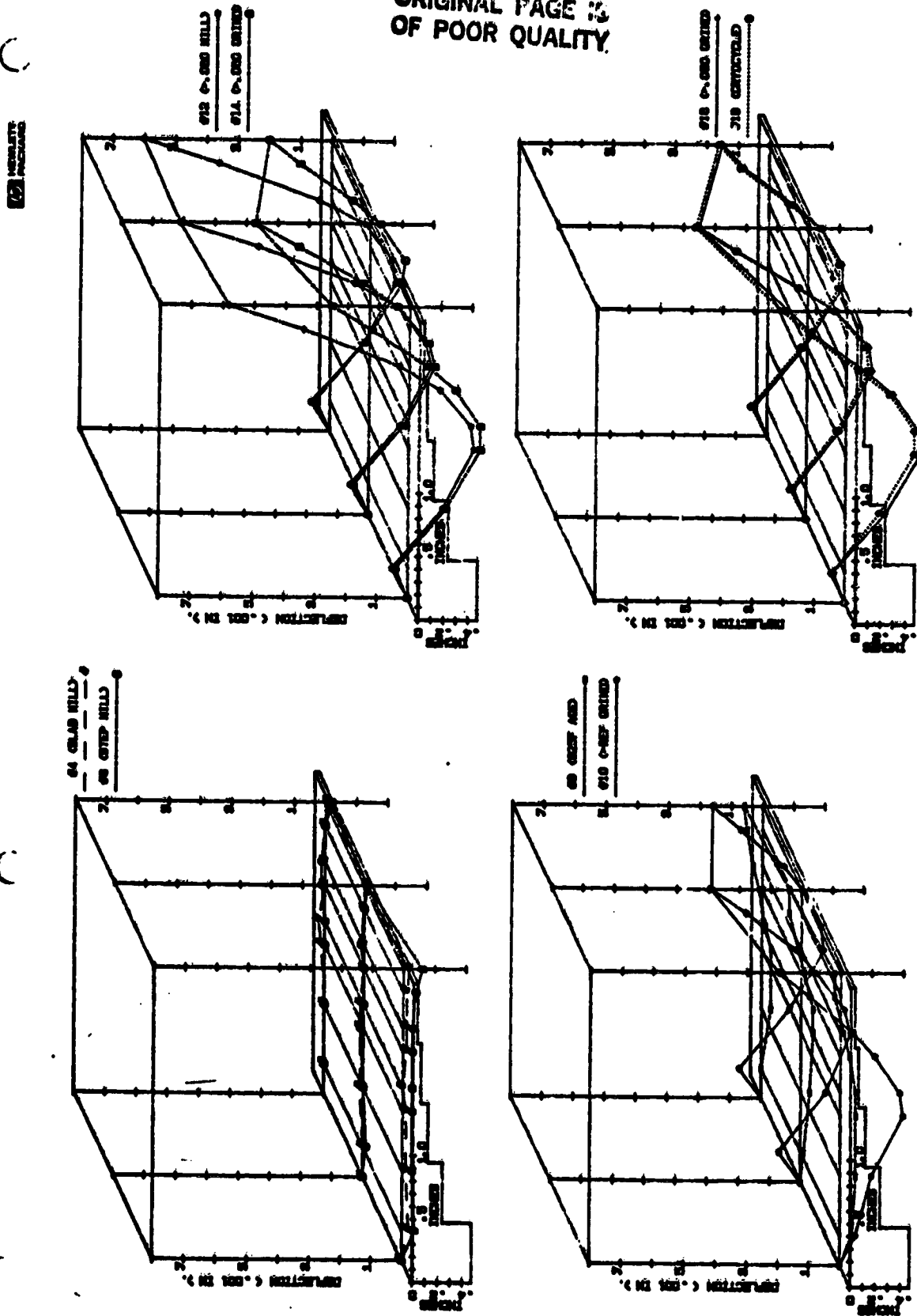


FIGURE 7. MATERIAL 18N1 200 GRADE SPECIMEN LC (LONGITUDINAL, CENTER)

REMARKS

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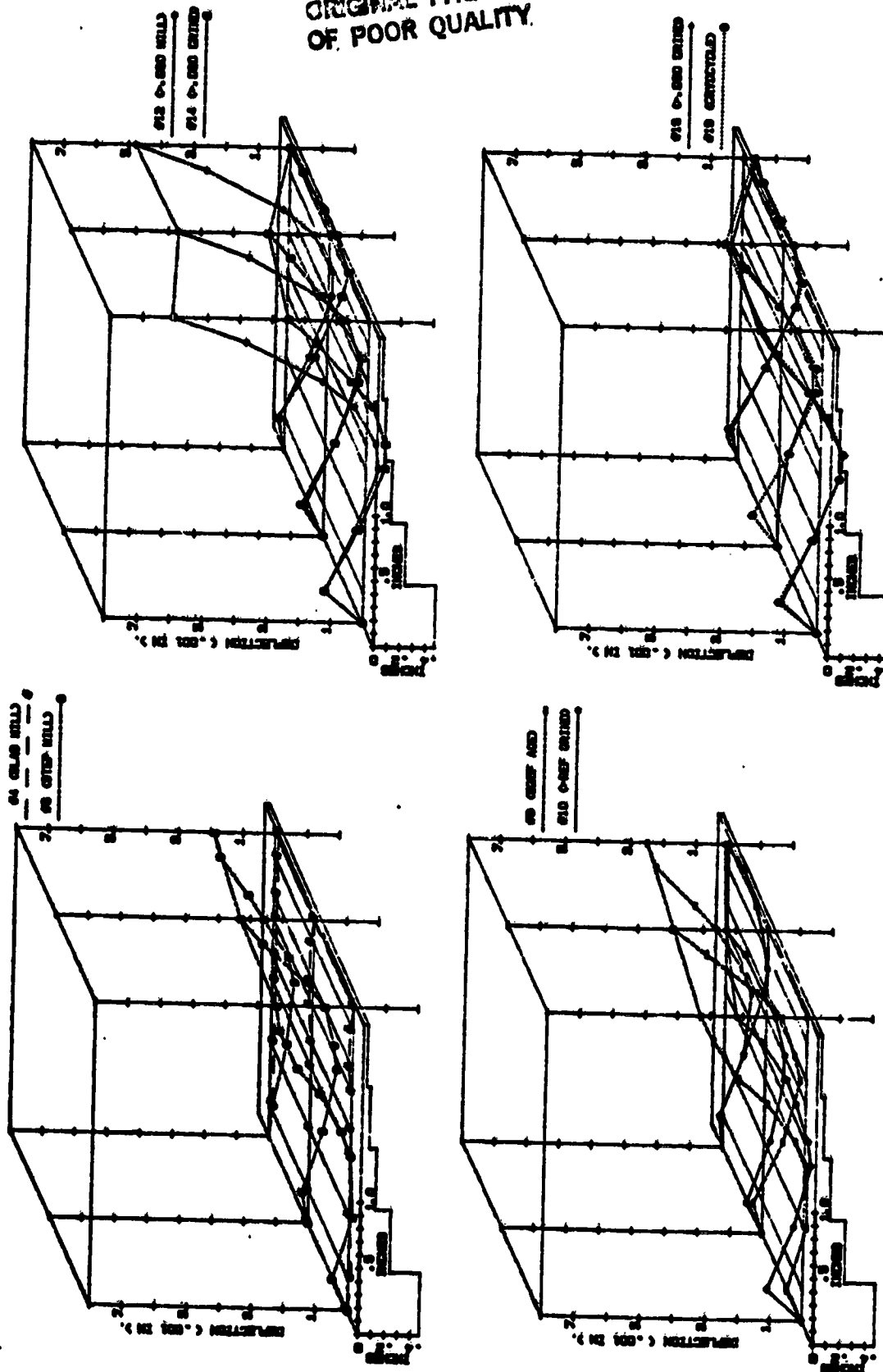


FIGURE 8. MATERIAL 18N1 200 GRADE SPECIMEN TS (TRANSVERSE, SURFACE)

MINI-MAX

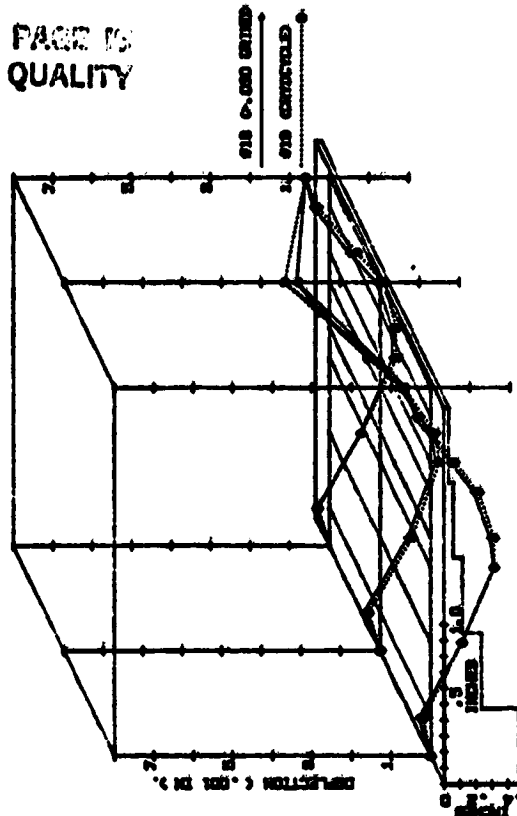
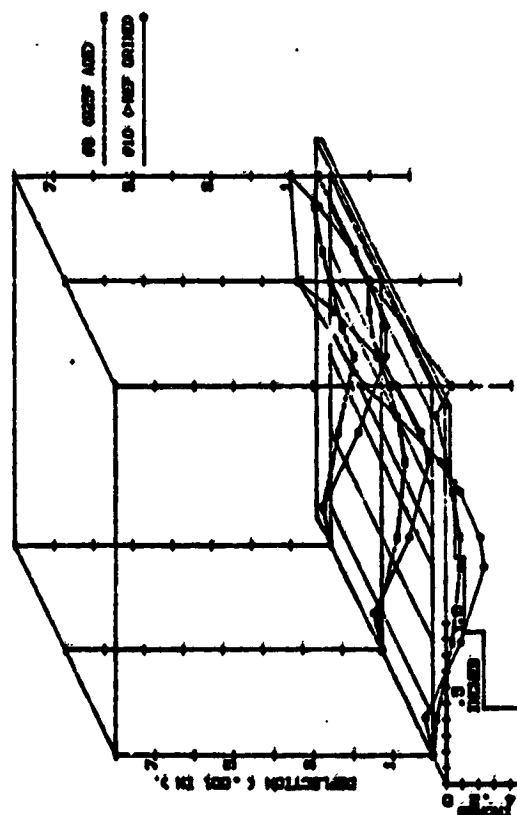
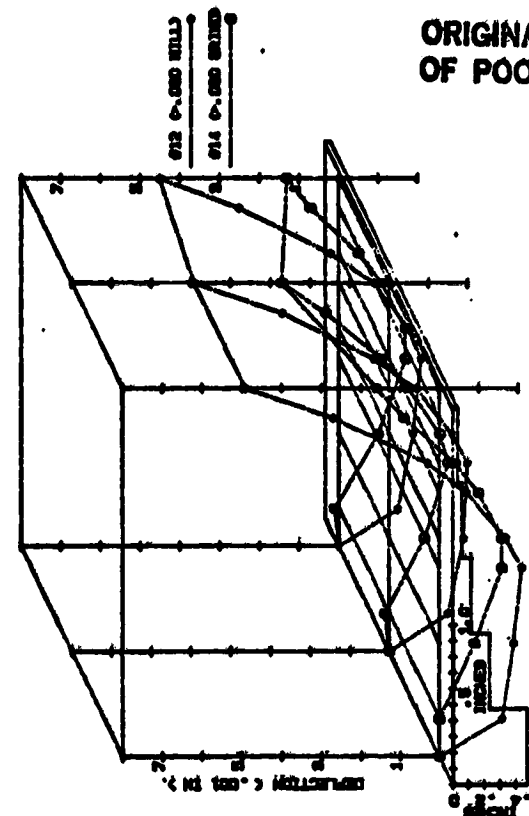
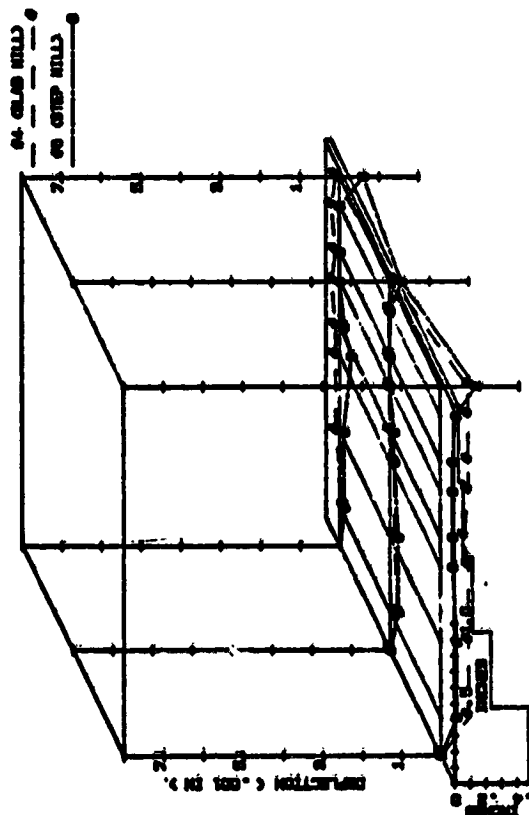


FIGURE 9. MATERIAL 18N1 200 GRADE SPECIMEN TC (TRANSVERSE, CENTER)

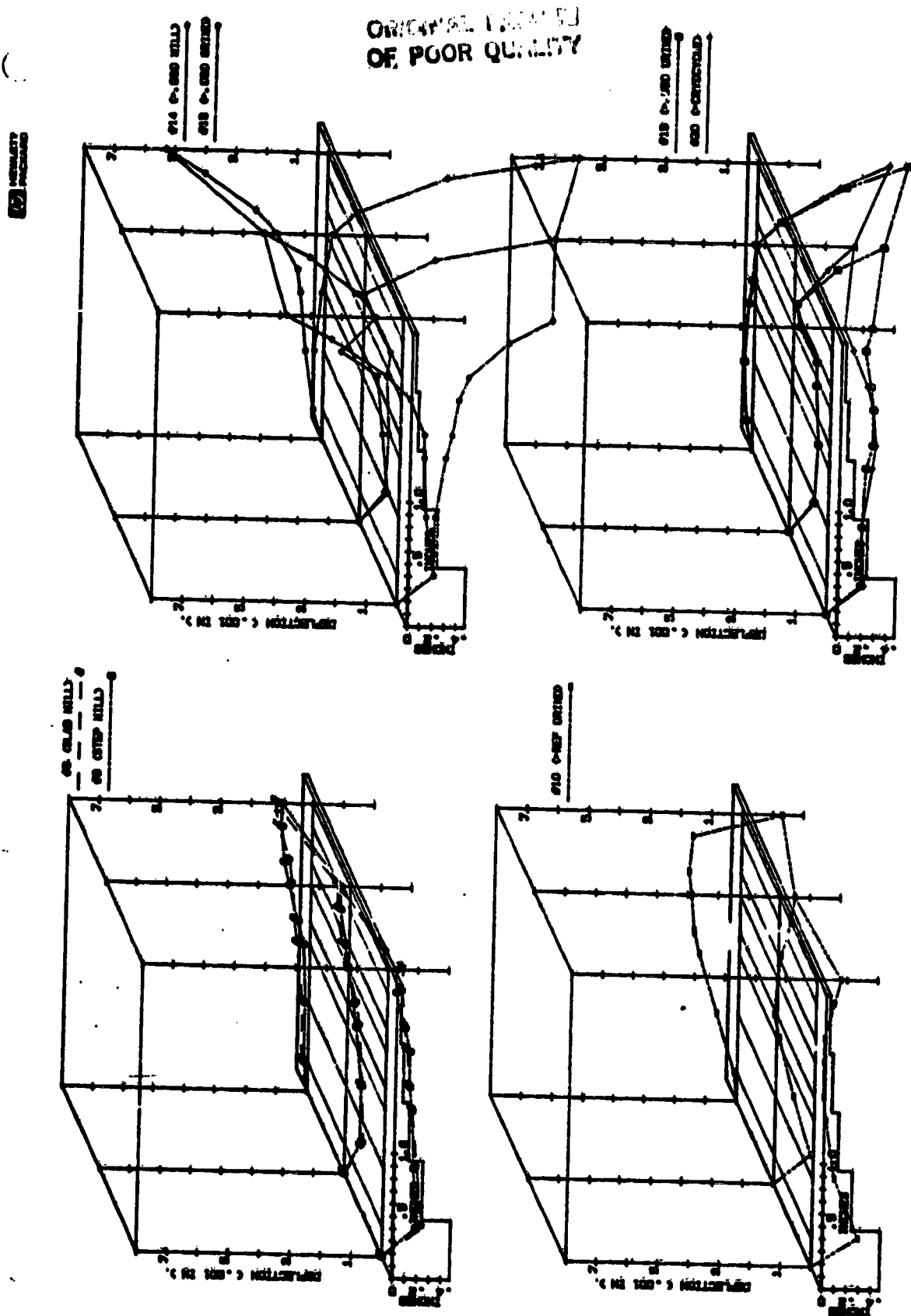


FIGURE 10. MATERIAL PH 13-8 NO SPECIMEN A-LSA (LONGITUDINAL, SURFACE ADDITIONAL)

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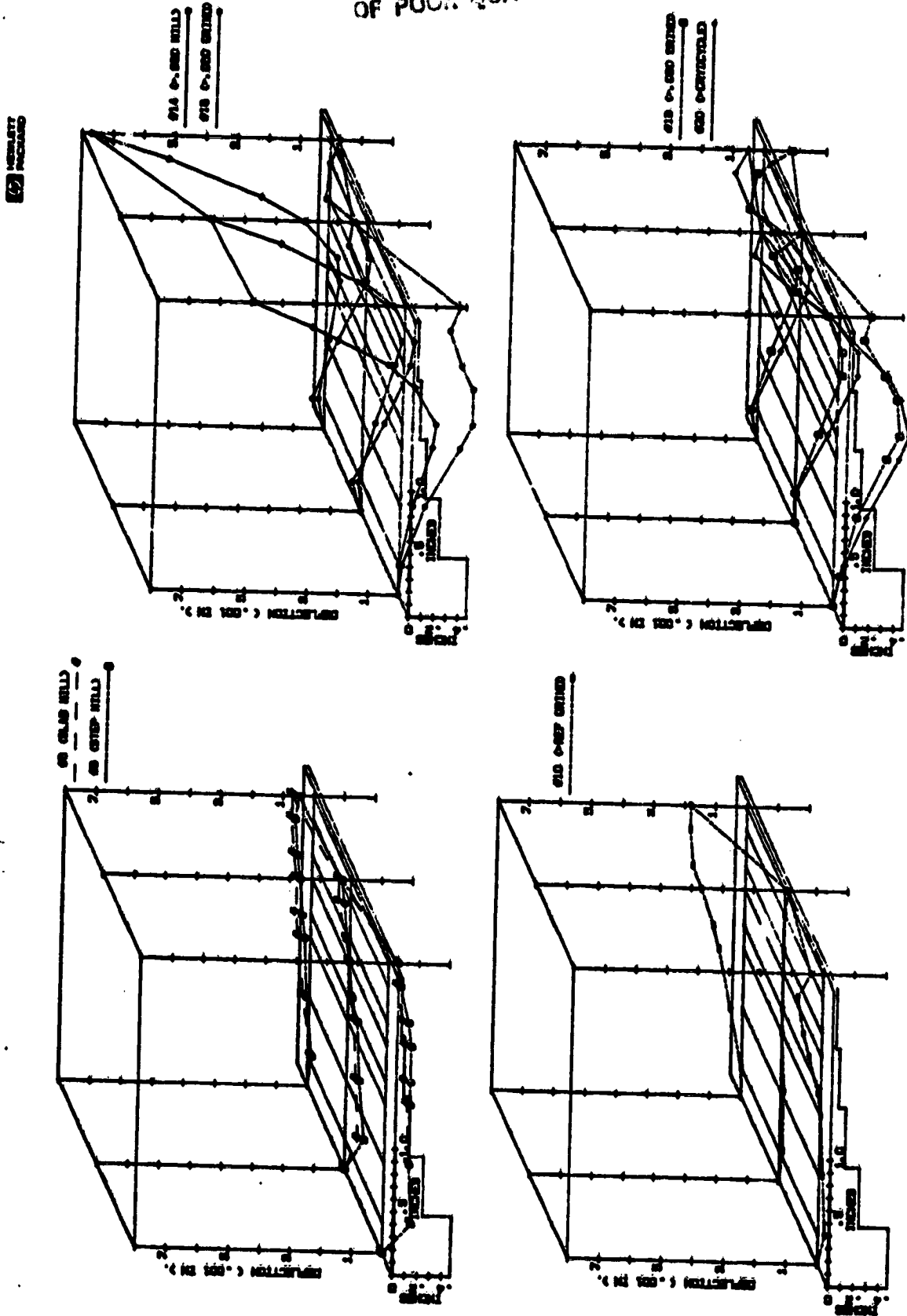


FIGURE 11. MATERIAL PH 13-8 NO SPECIMEN A-CLS (CONTROL, LONGITUDINAL, SURFACE)

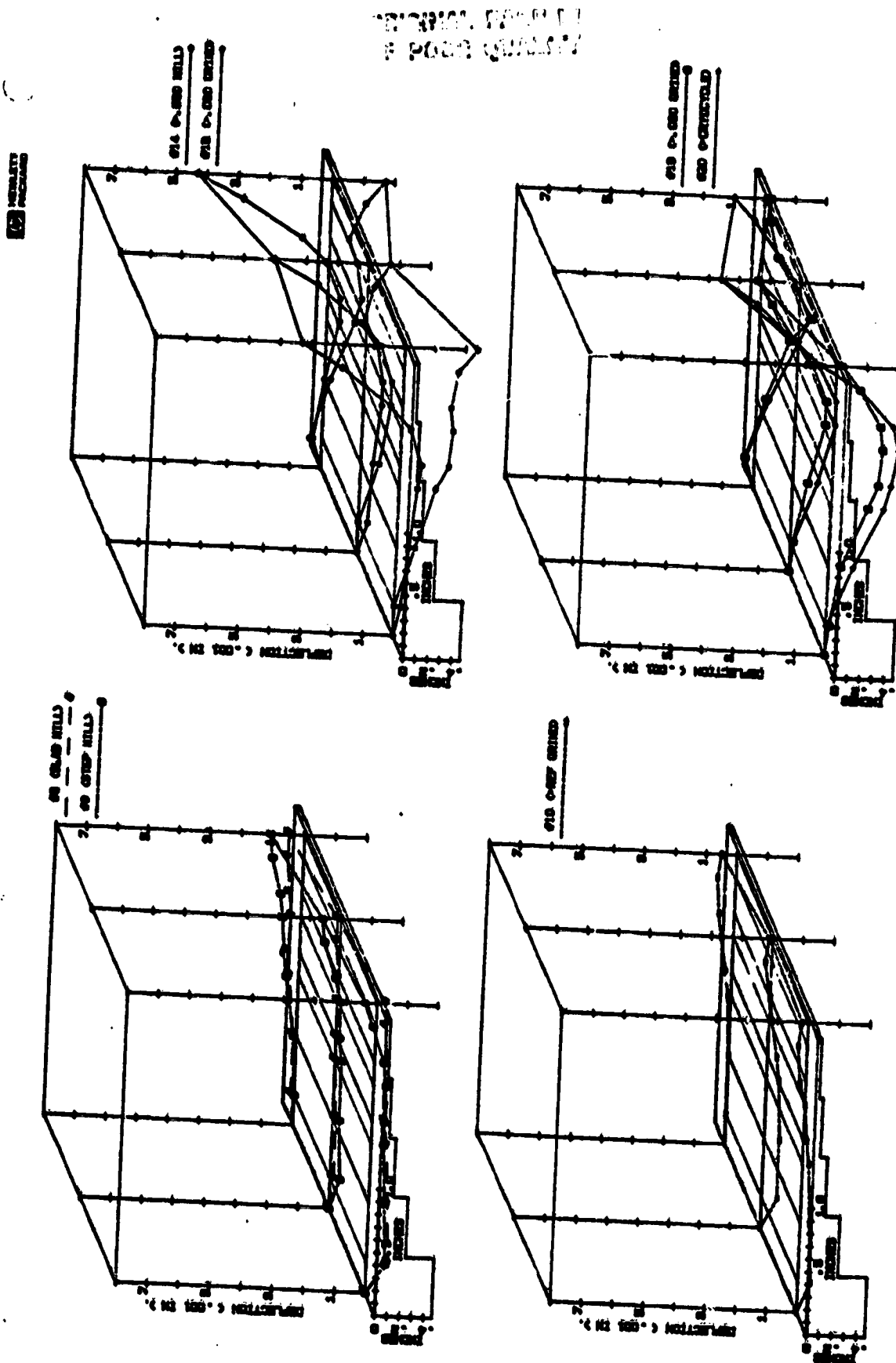


FIGURE 12. MATERIAL PH 13-8 NO SPECIMEN A-CLC (CONTROL, LONGITUDINAL, CENTER)

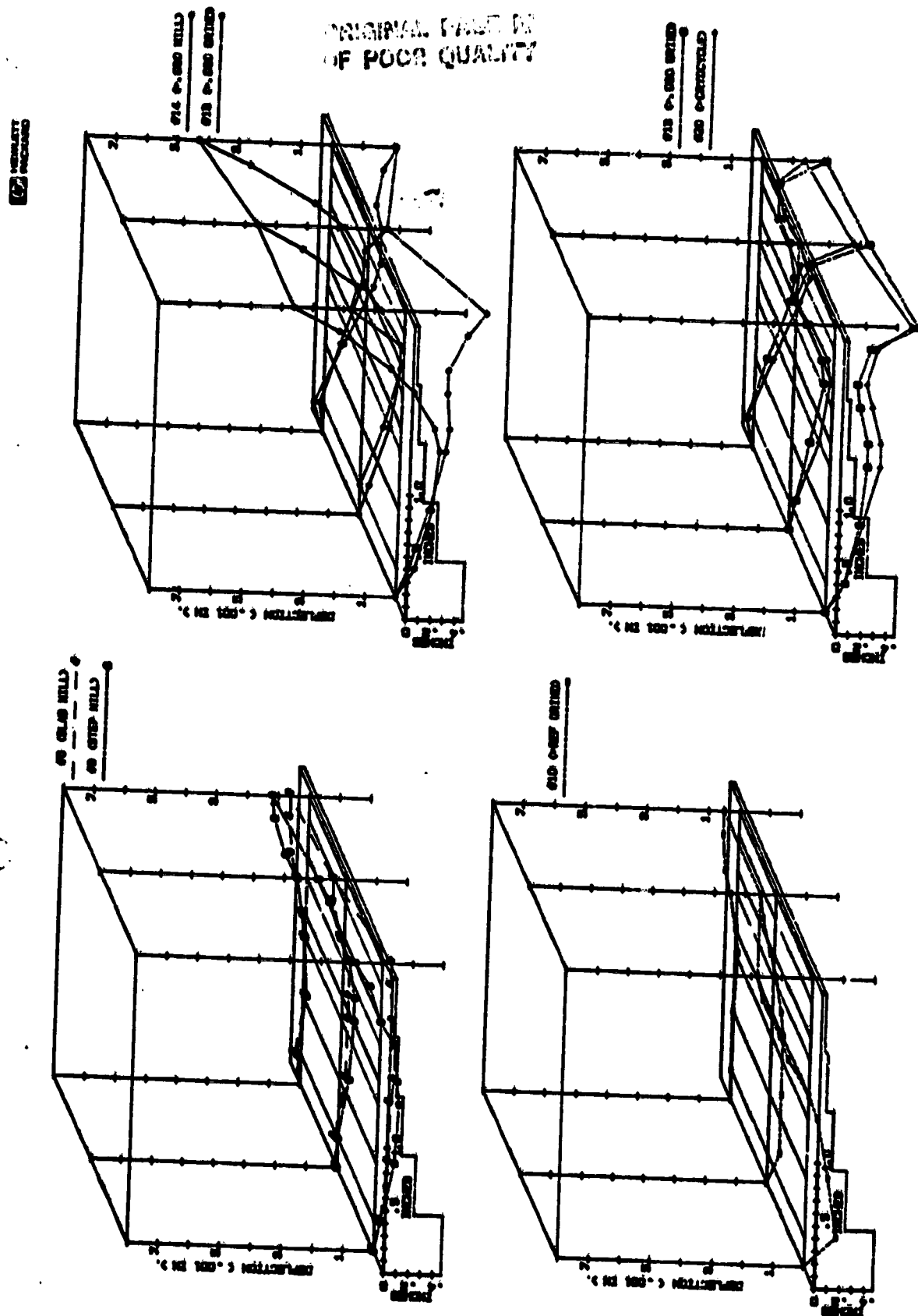


FIGURE 13. MATERIAL PH 13-8 NO SPECIMEN A-LS (LONGITUDINAL, SURFACE)

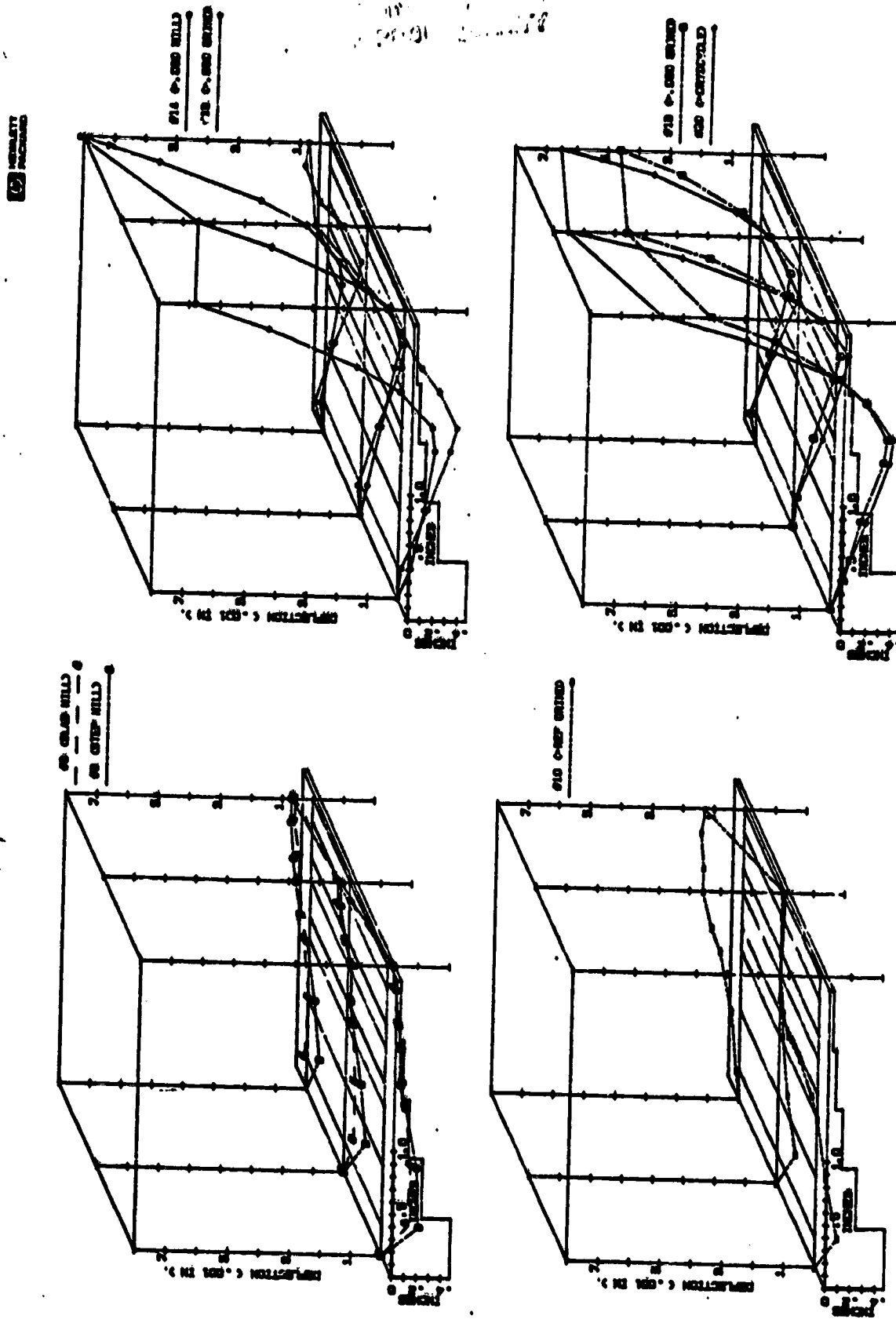


FIGURE 15. MATERIAL PH 13-8 MO SPECIMEN A-TS (TRANSVERSE, SURFACE)

MEMBER

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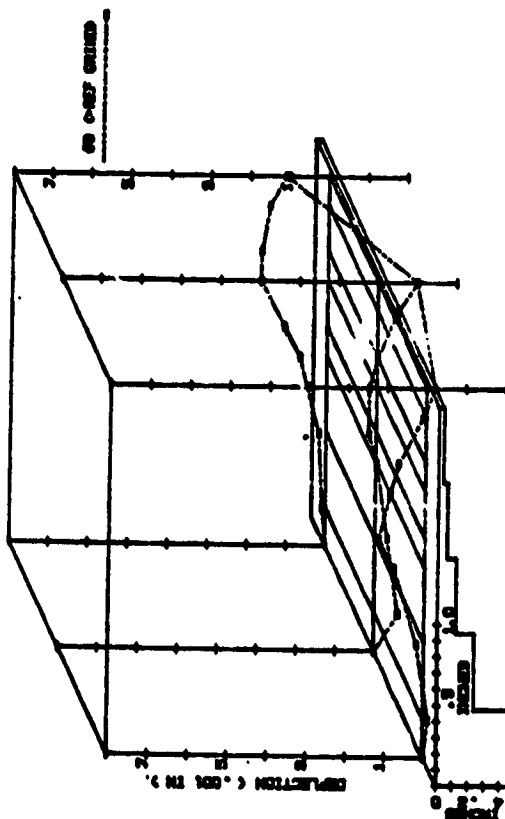
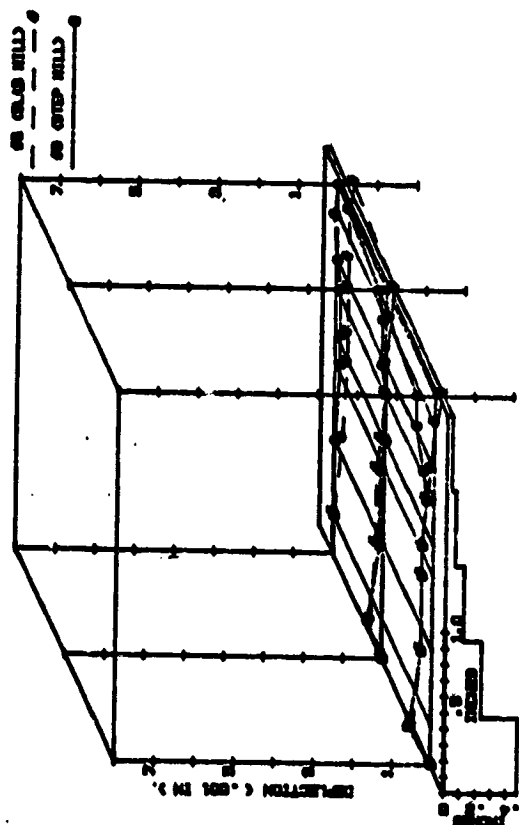
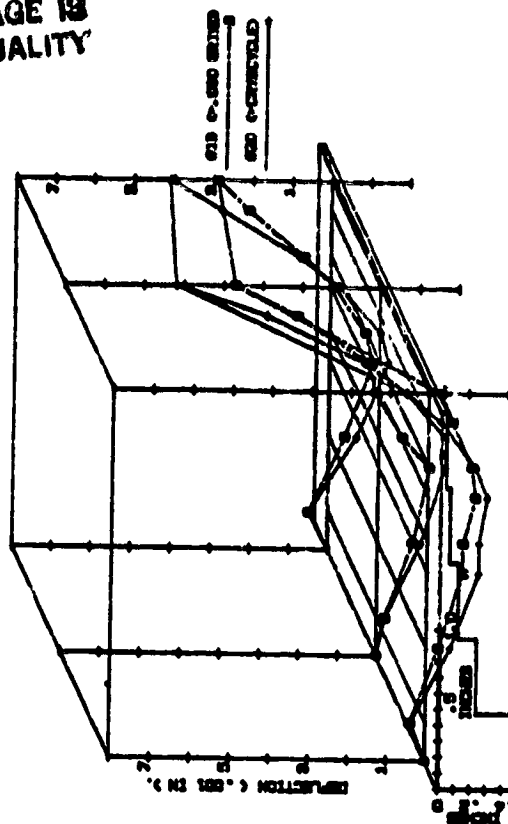
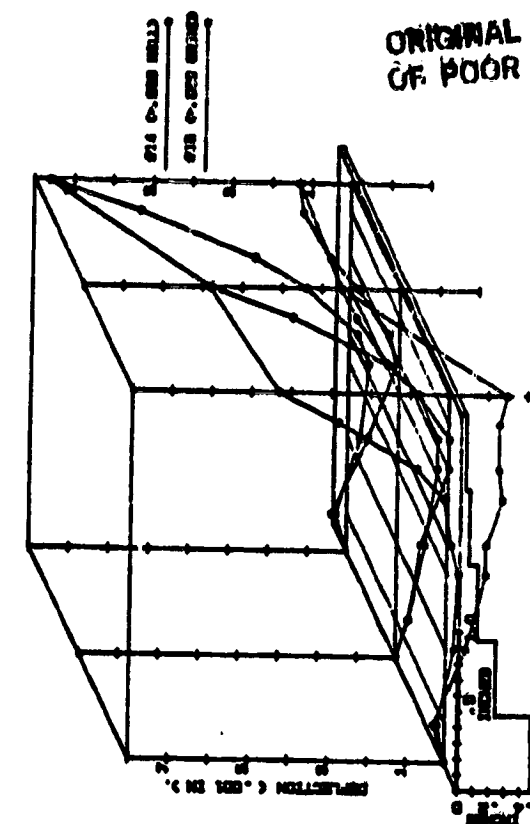


FIGURE 16. MATERIAL PH 13-8 MO SPECIMEN A-TC (TRANSVERSE, CENTER)

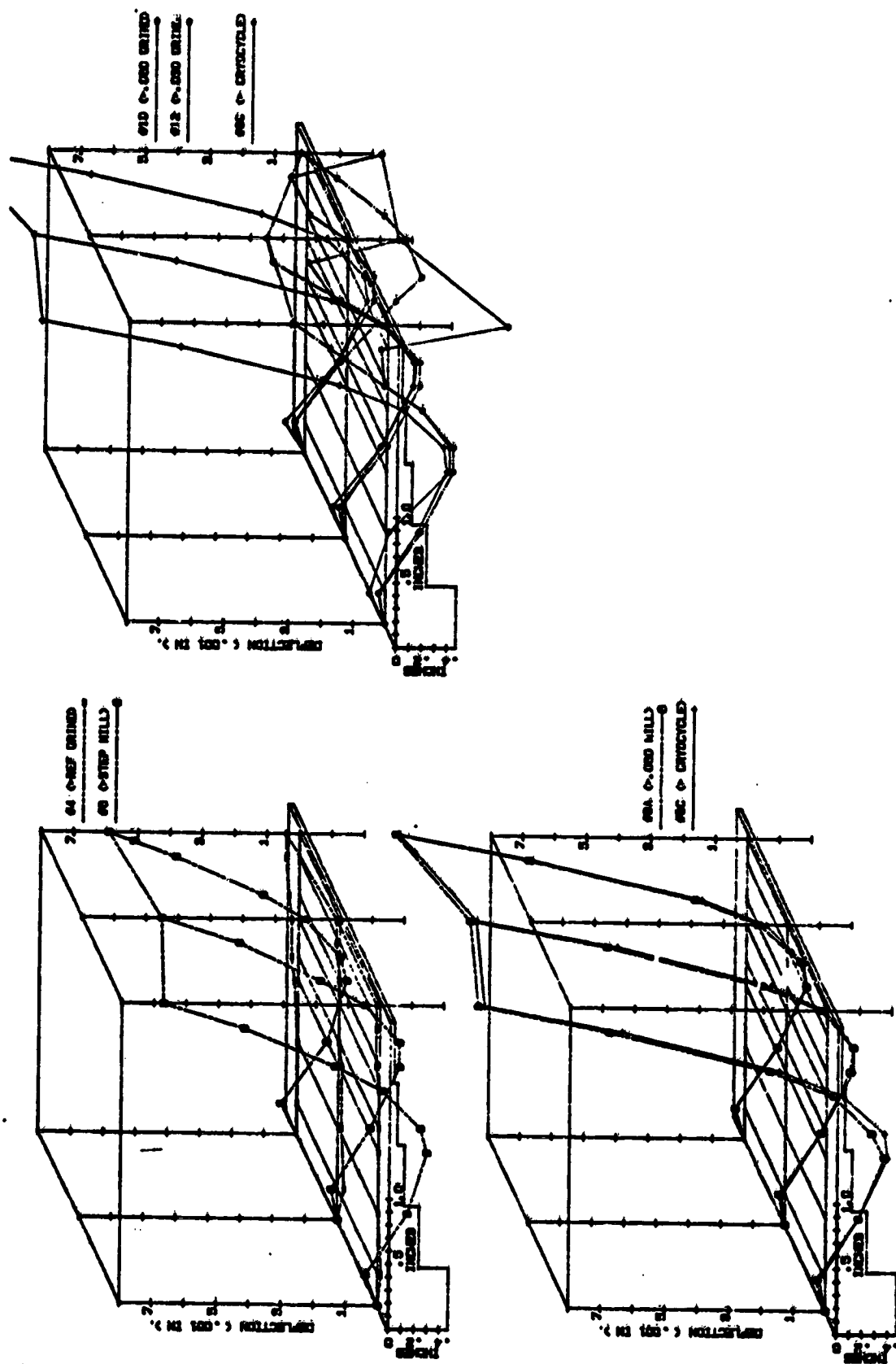


FIGURE 1/. MATERIAL A286 SS SPECIMEN LS (LONGITUDINAL, SURFACE)

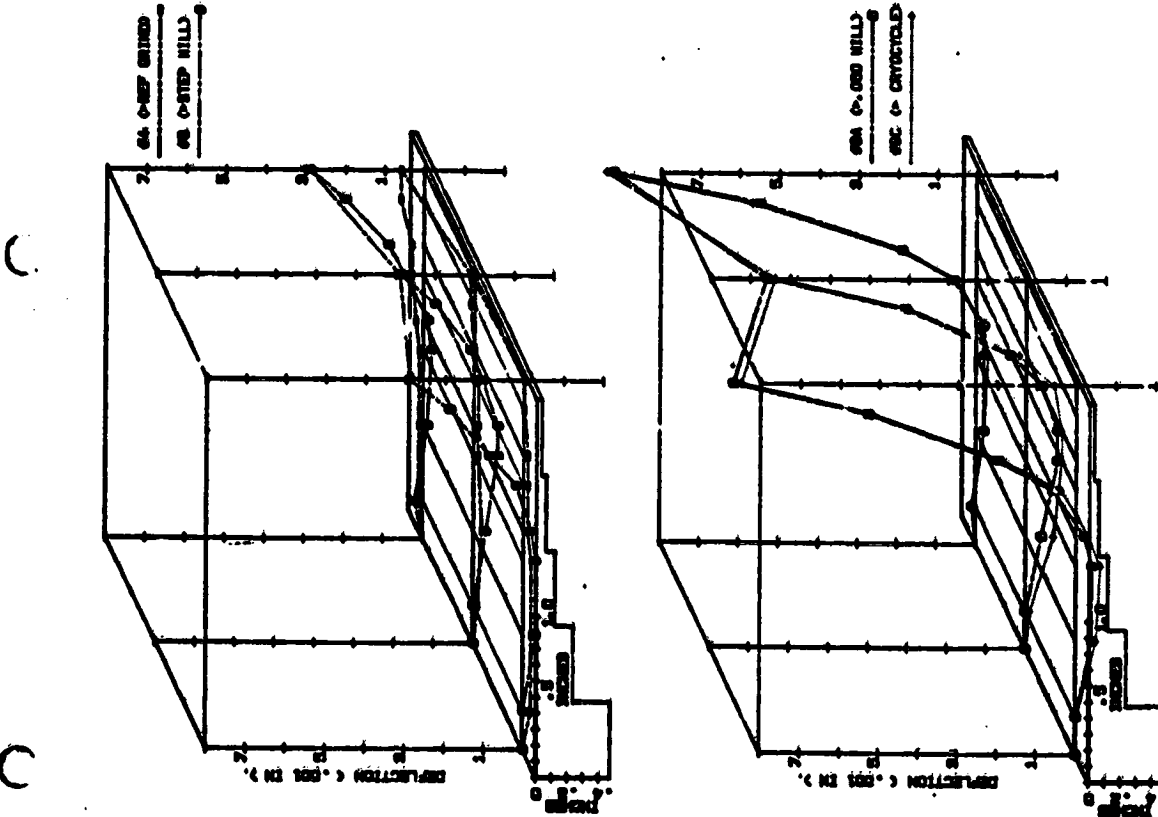
[illegible]

FIGURE 18. MATERIAL A286 SS SPECIMEN LC (LONGITUDINAL, CENTER)

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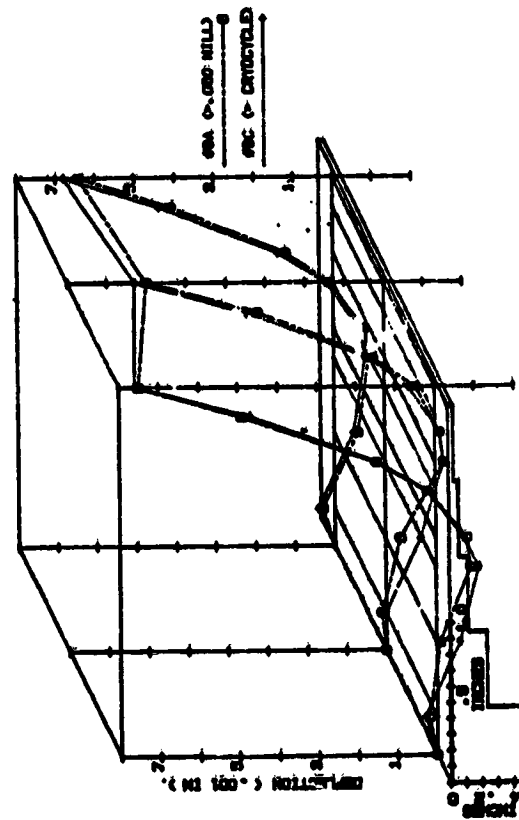
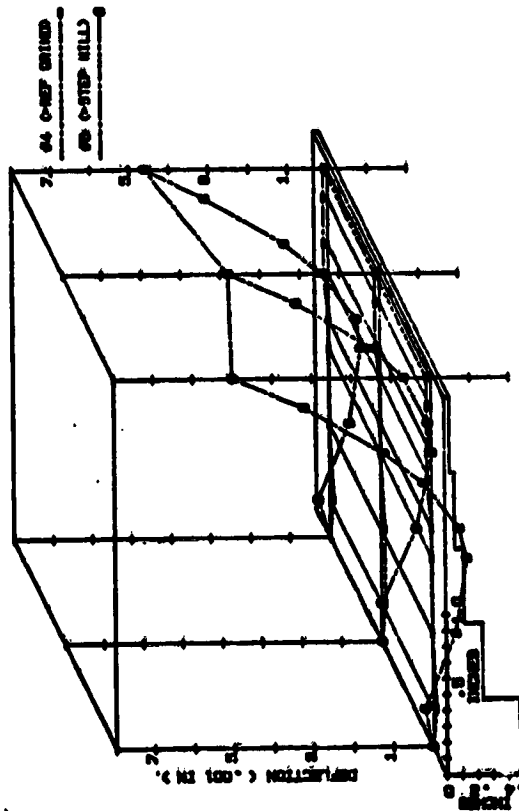
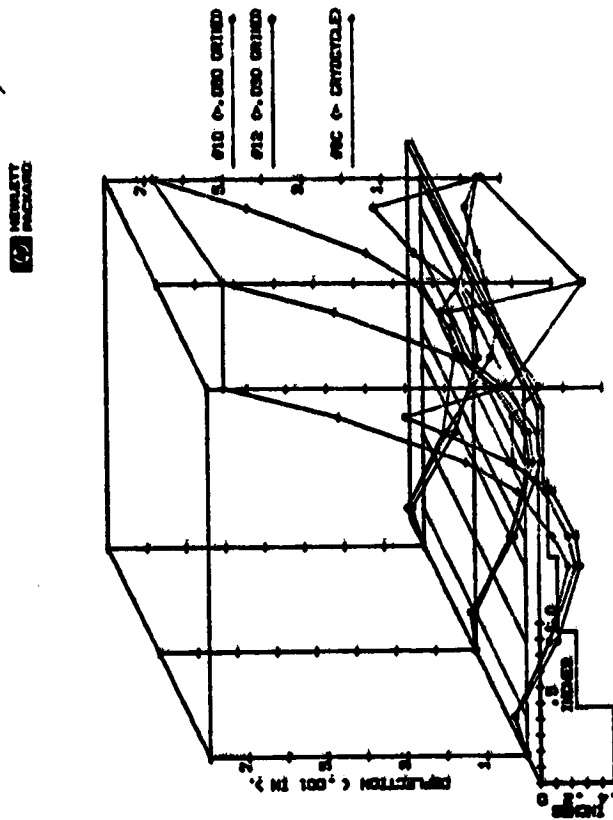


FIGURE 19- MATERIAL A286 SS SPECIMEN TS (TRANSVERSE, SURFACE)

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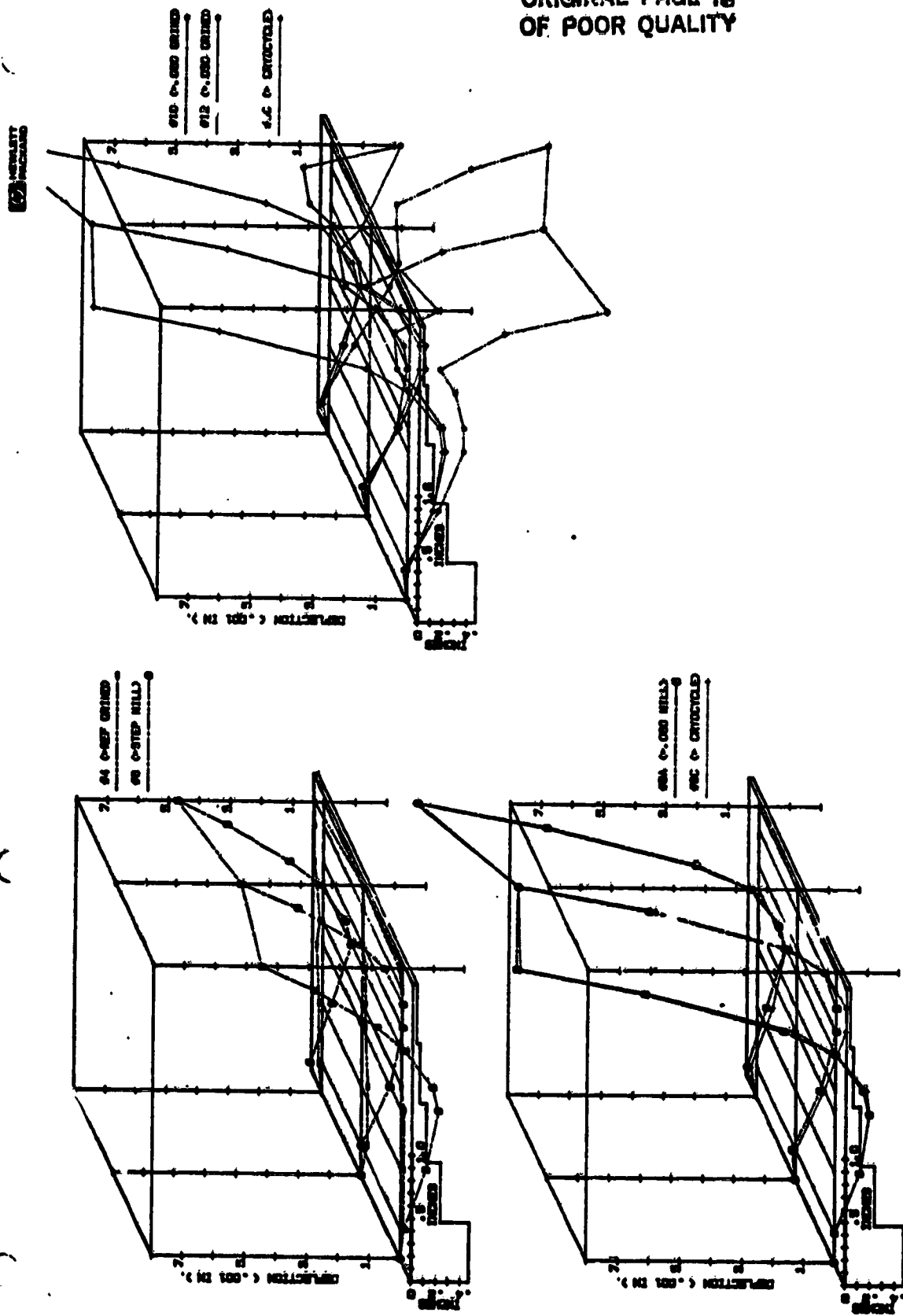
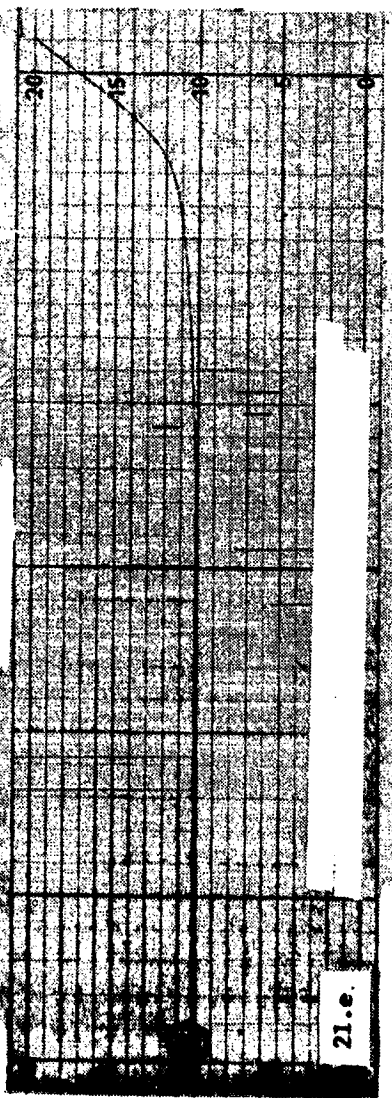
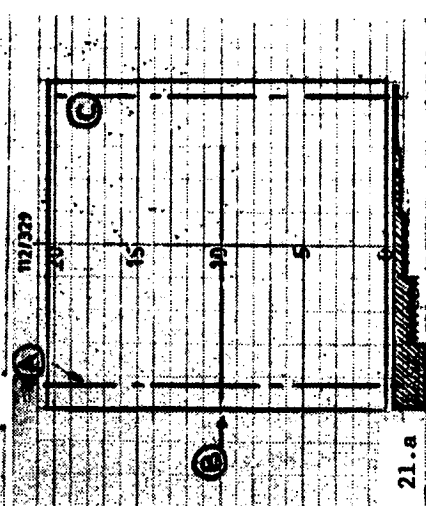
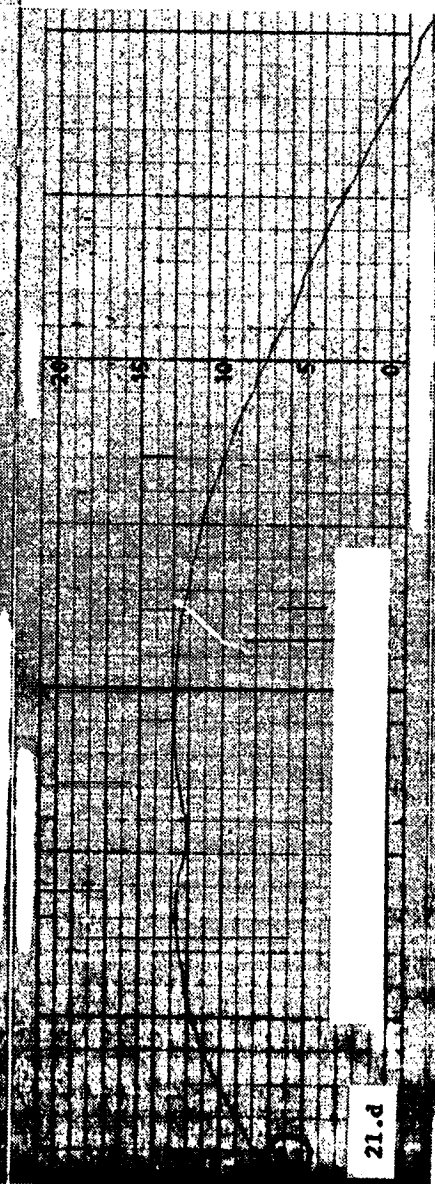
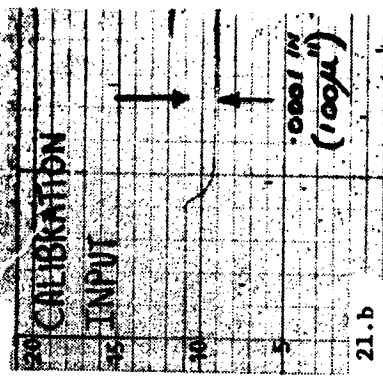
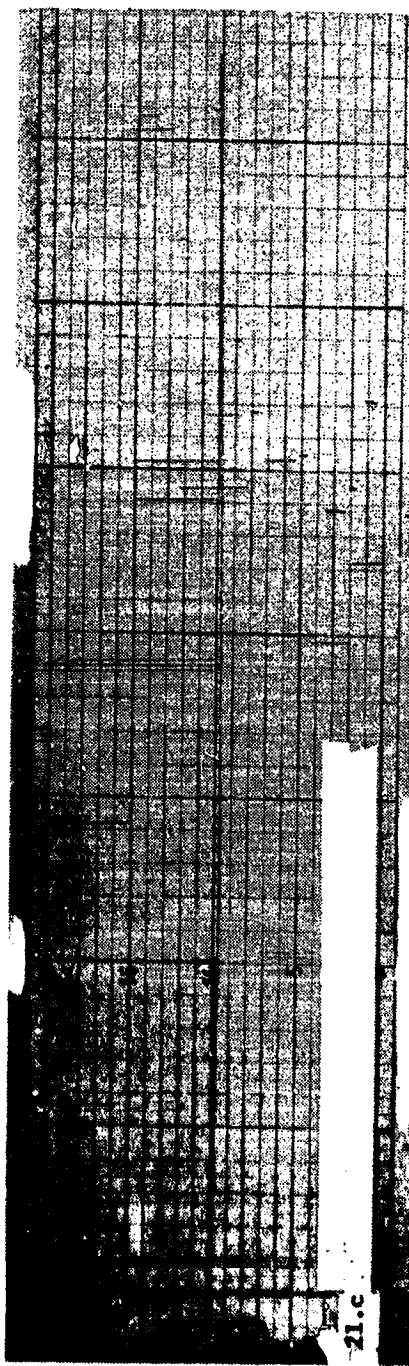


FIGURE 20- MATERIAL A286 SS SPECIMEN TC (TRANSVERSE, CENTER)



ORIENTATION OF TRACES

FIGURE 21. TALYSURF TRACES FOR 18N1 200 GRADE, SAMPLE SOTON 1

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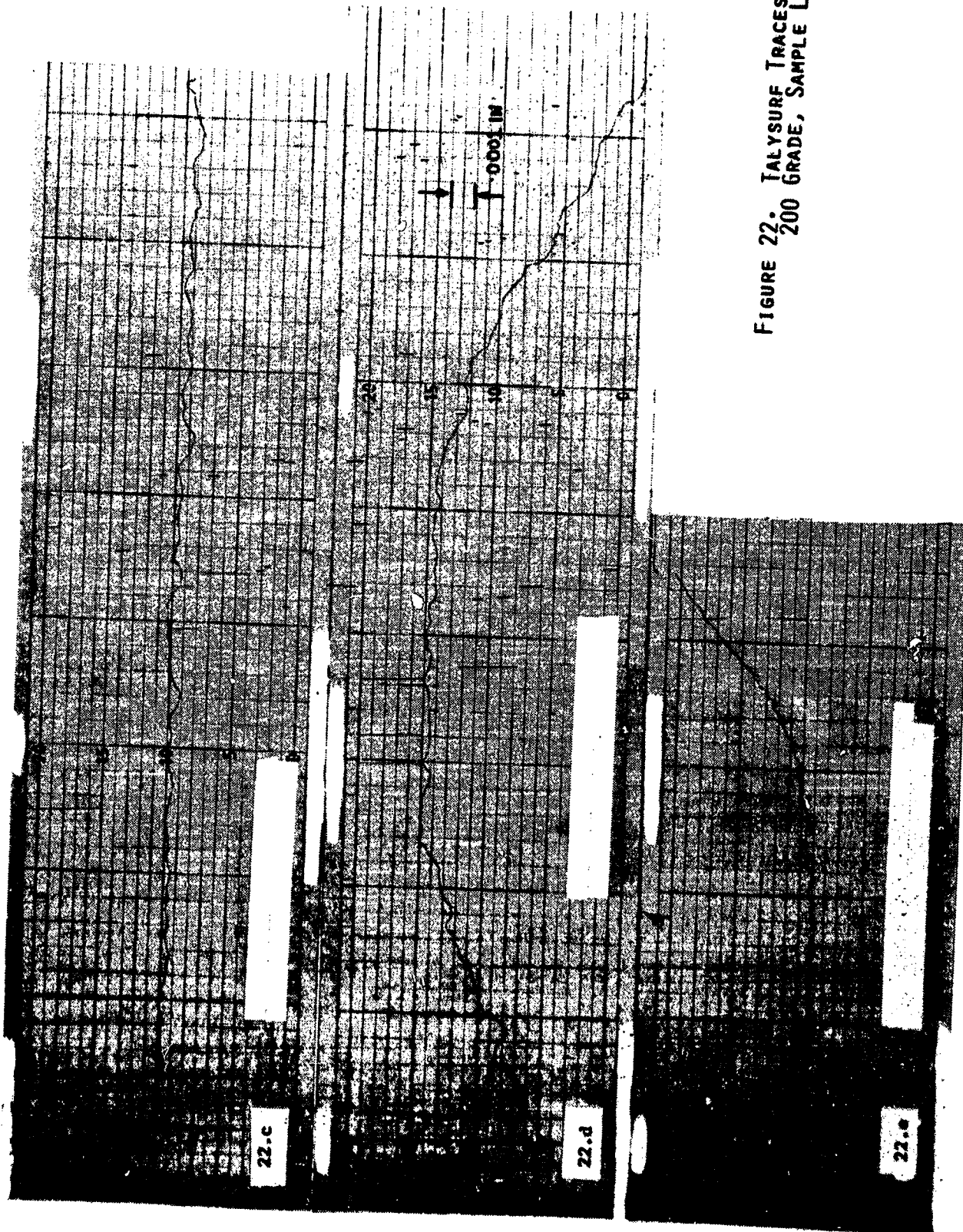


FIGURE 22. TALYSURF TRACES FOR 18N1
200 GRADE, SAMPLE LC

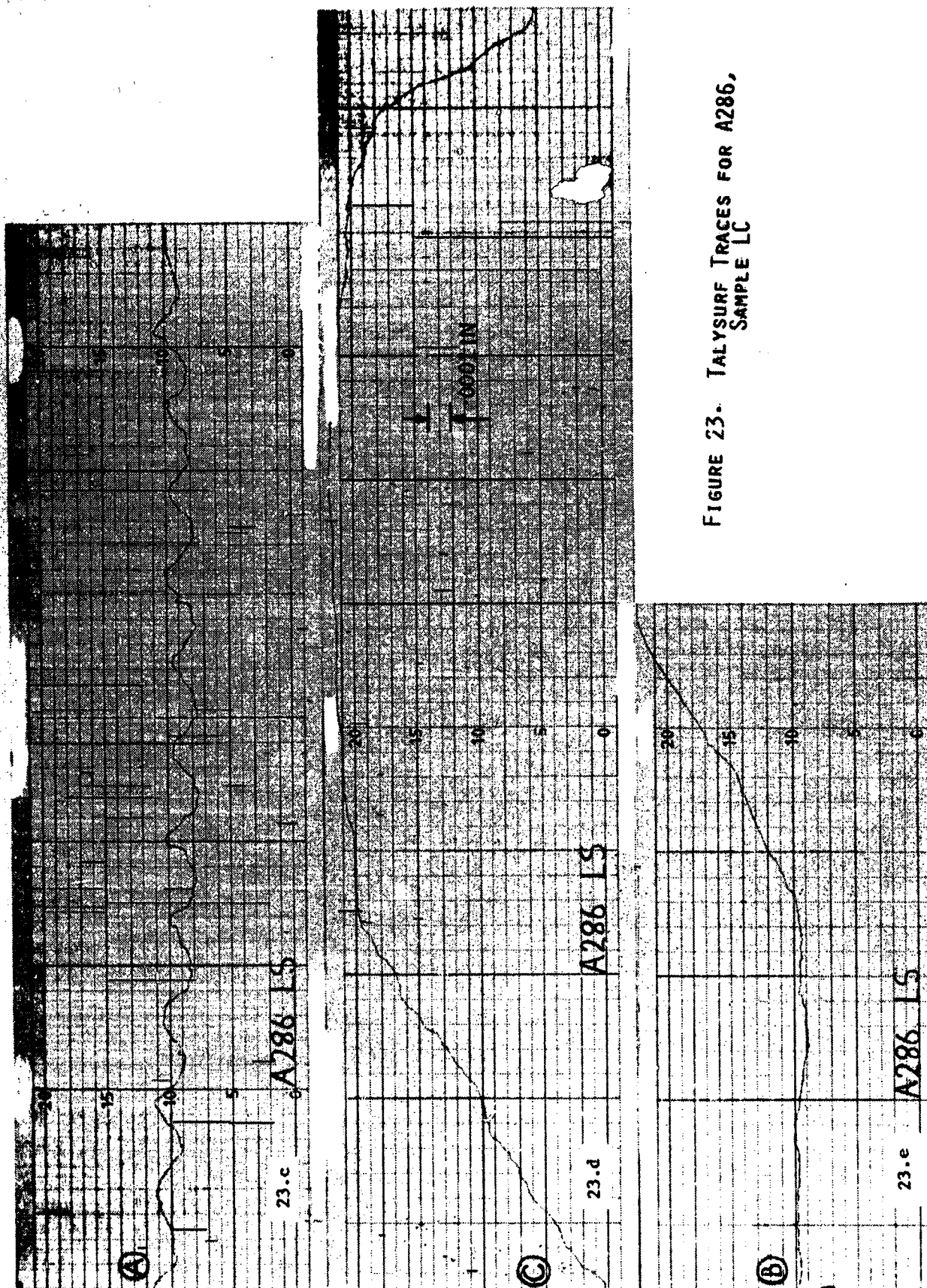


FIGURE 23. TALYSURF TRACES FOR A286,
SAMPLE LC

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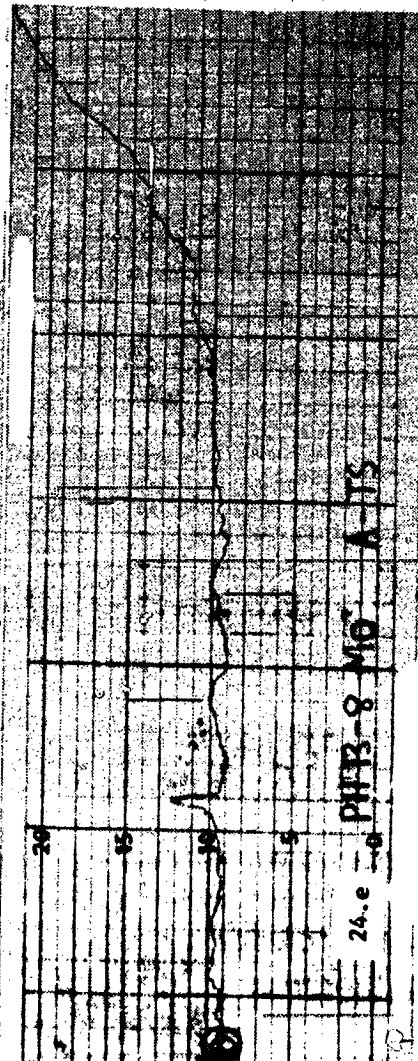
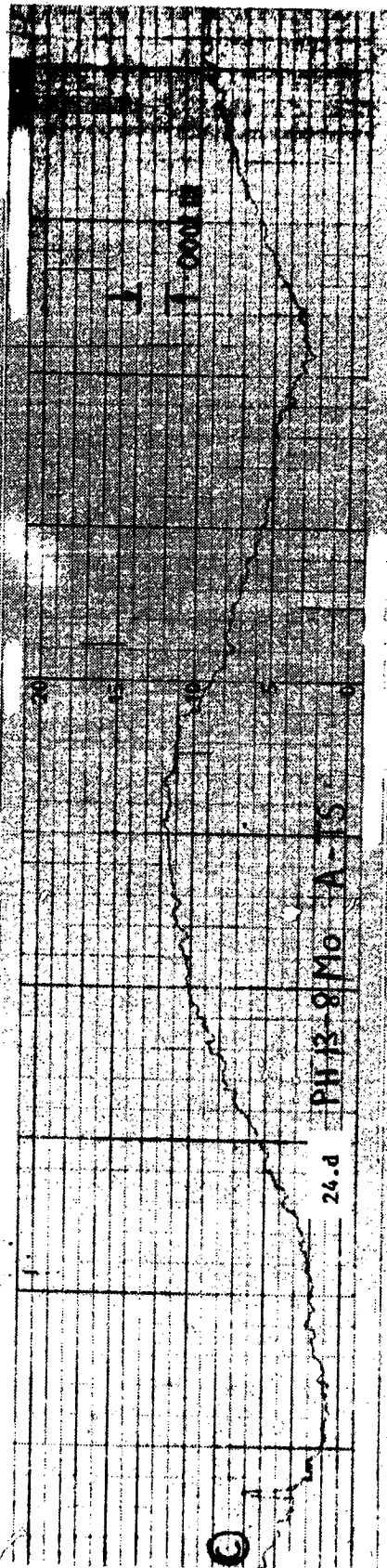
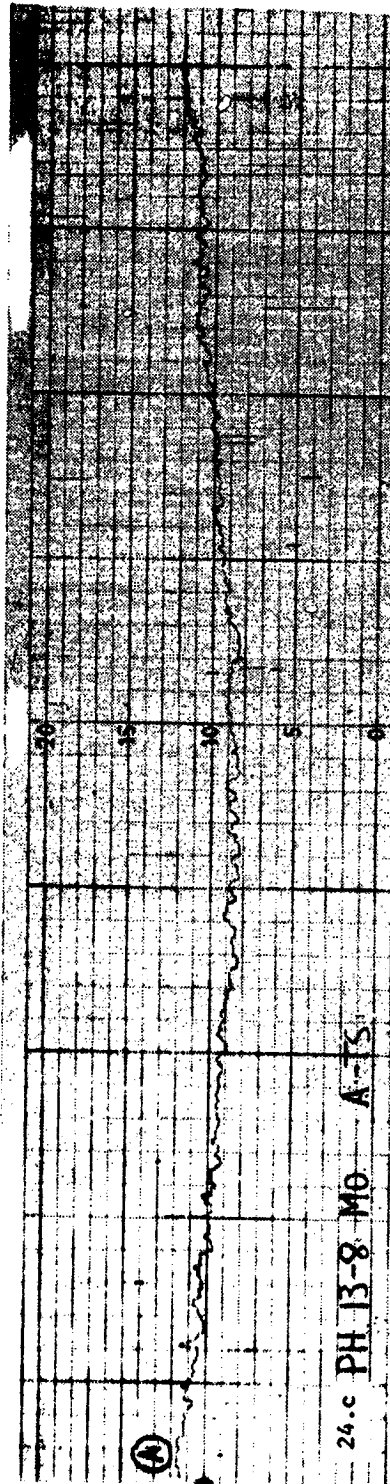


FIGURE 24: TALYSURF TRACES FOR
PH 13-8 MO, SAMPLE A-TS

DEFLECTION
— .003 (INCHES)

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— .002

— .001

3

2

1

3 (.0023)

2 (.0032)

1 (.0036)

↑
12 → 6 mm
STEP

↑
6 → 3 mm.
STEP

↑
3 → 1.5 mm
STEP

↑
1.5 → 0.75 mm
STEP

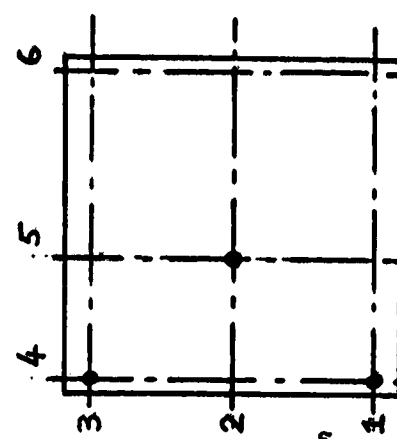


FIGURE 25. MATERIAL 18N1 200 GRADE SPECIMEN SOTON 1

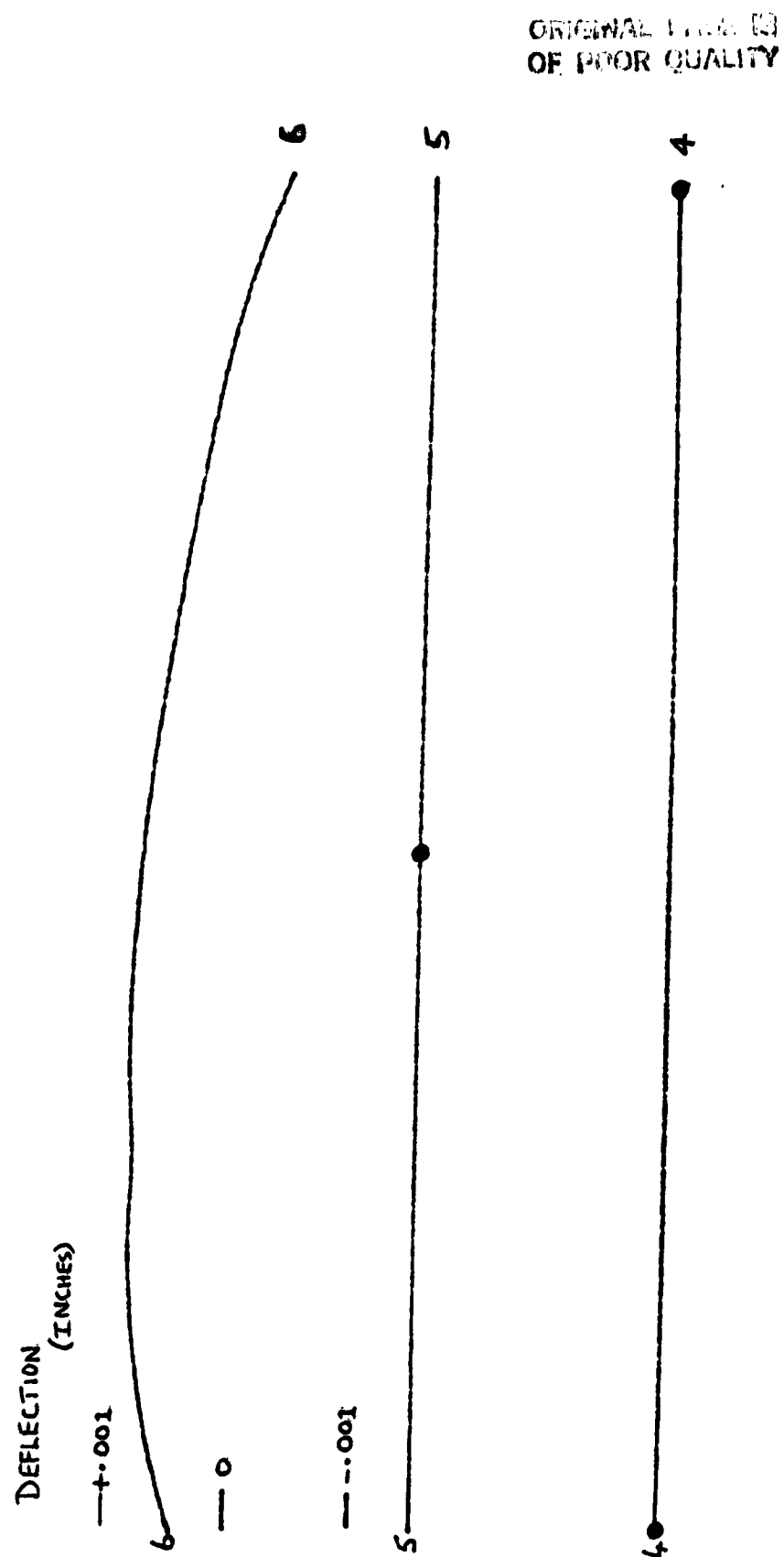


FIGURE 26. MATERIAL 18N1 200 GRADE SPECIMEN SUTON 1

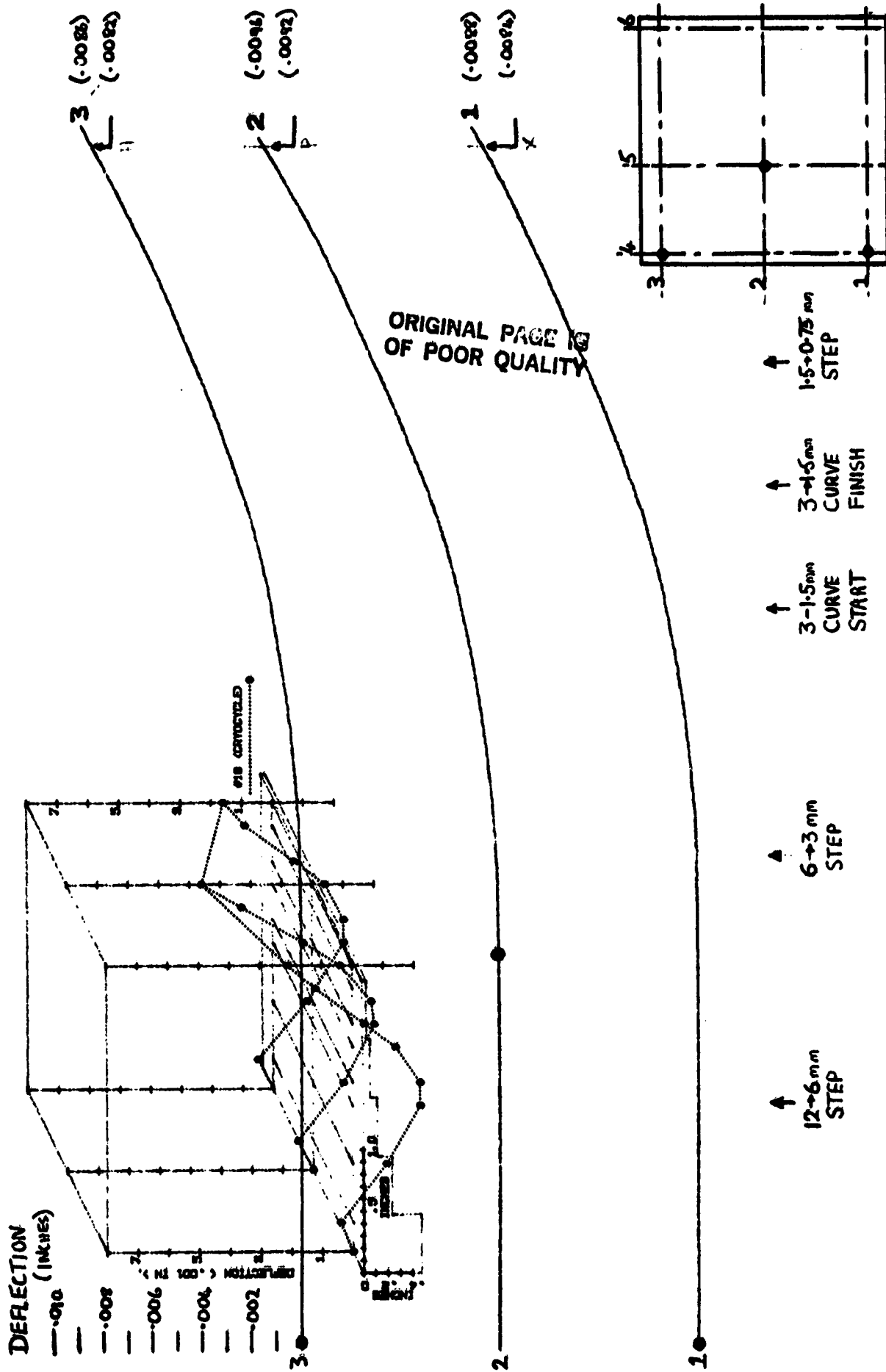


FIGURE 27. MATERIAL 18N1 200 GRADE SPECIMEN LC (LONGITUDINAL, CENTER)

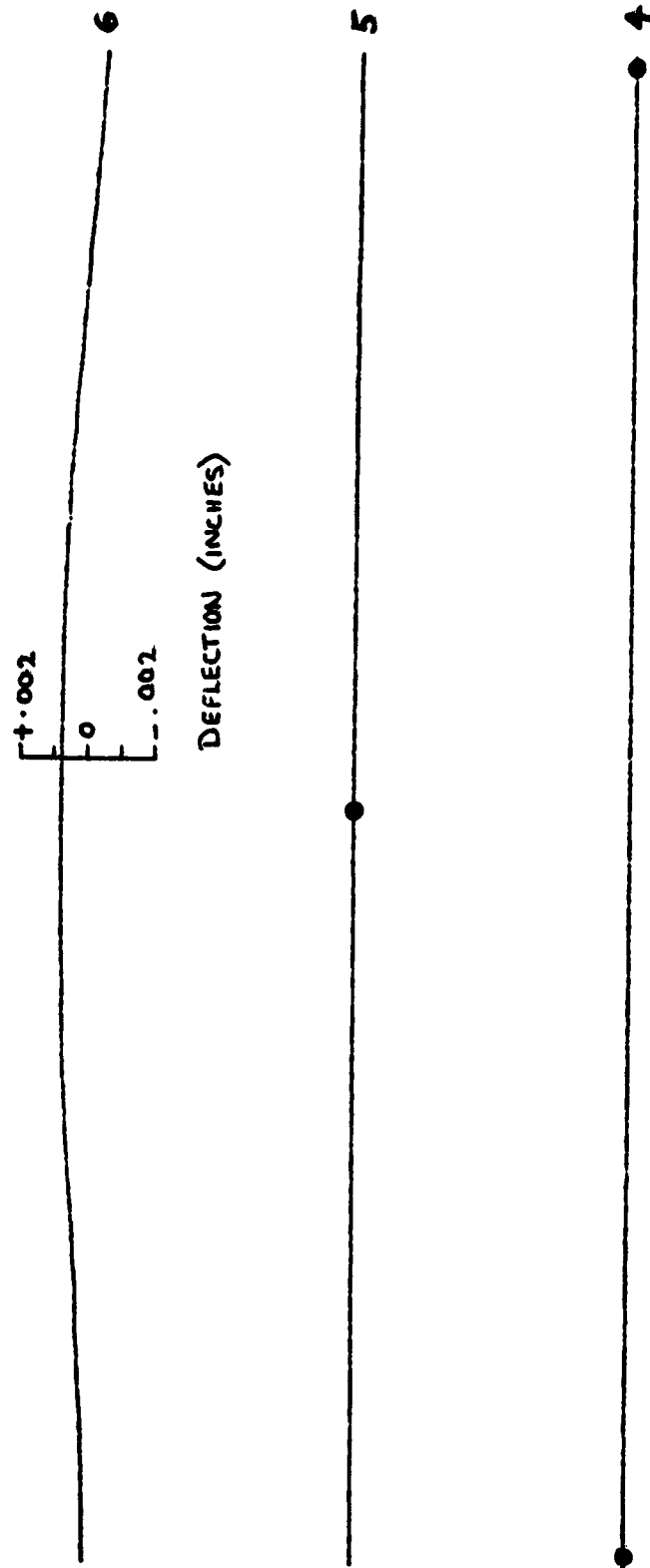


FIGURE 28. MATERIAL 18N: 200 GRADE SPECIMEN LC (LONGITUDINAL, CENTER)

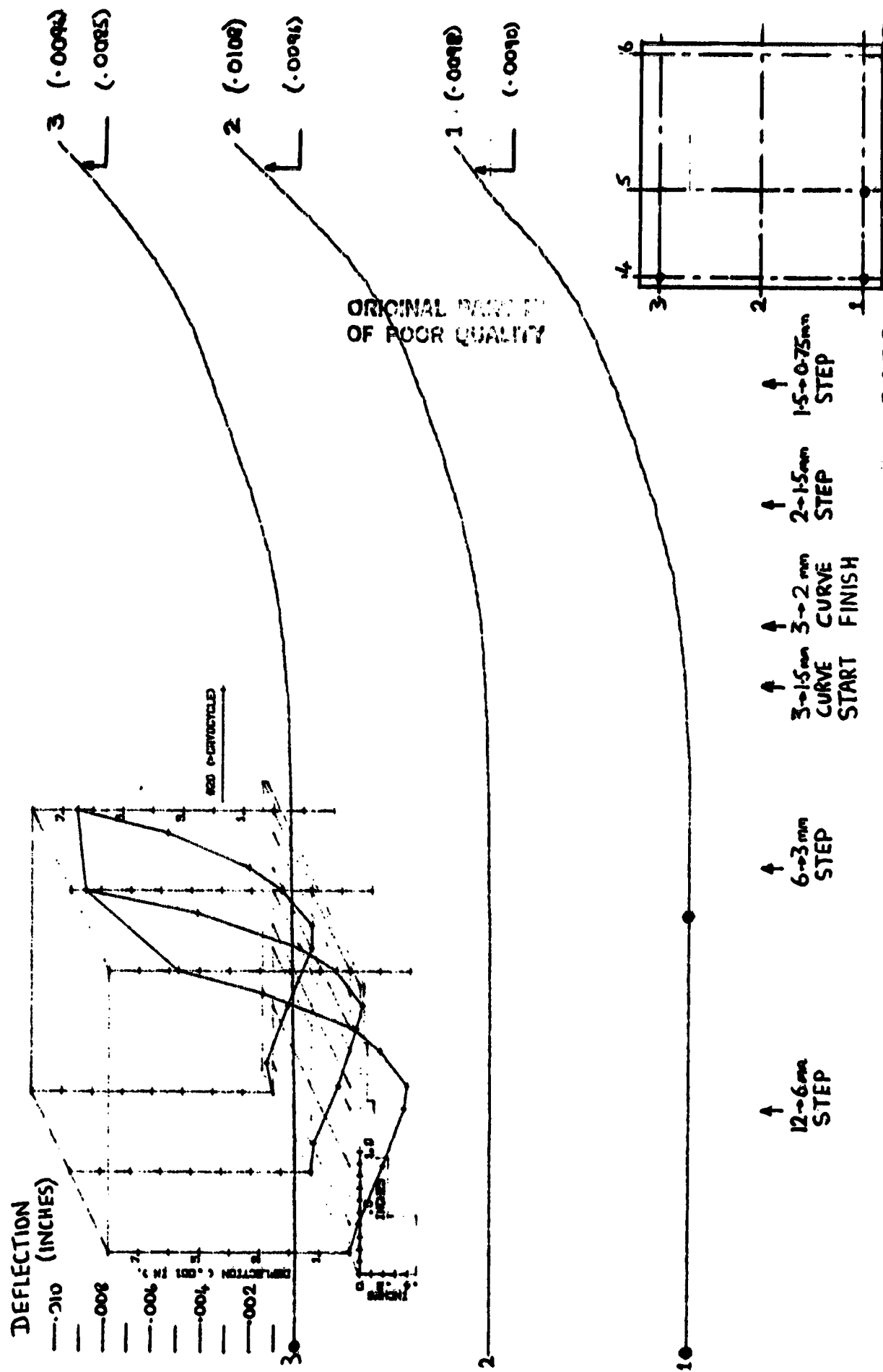
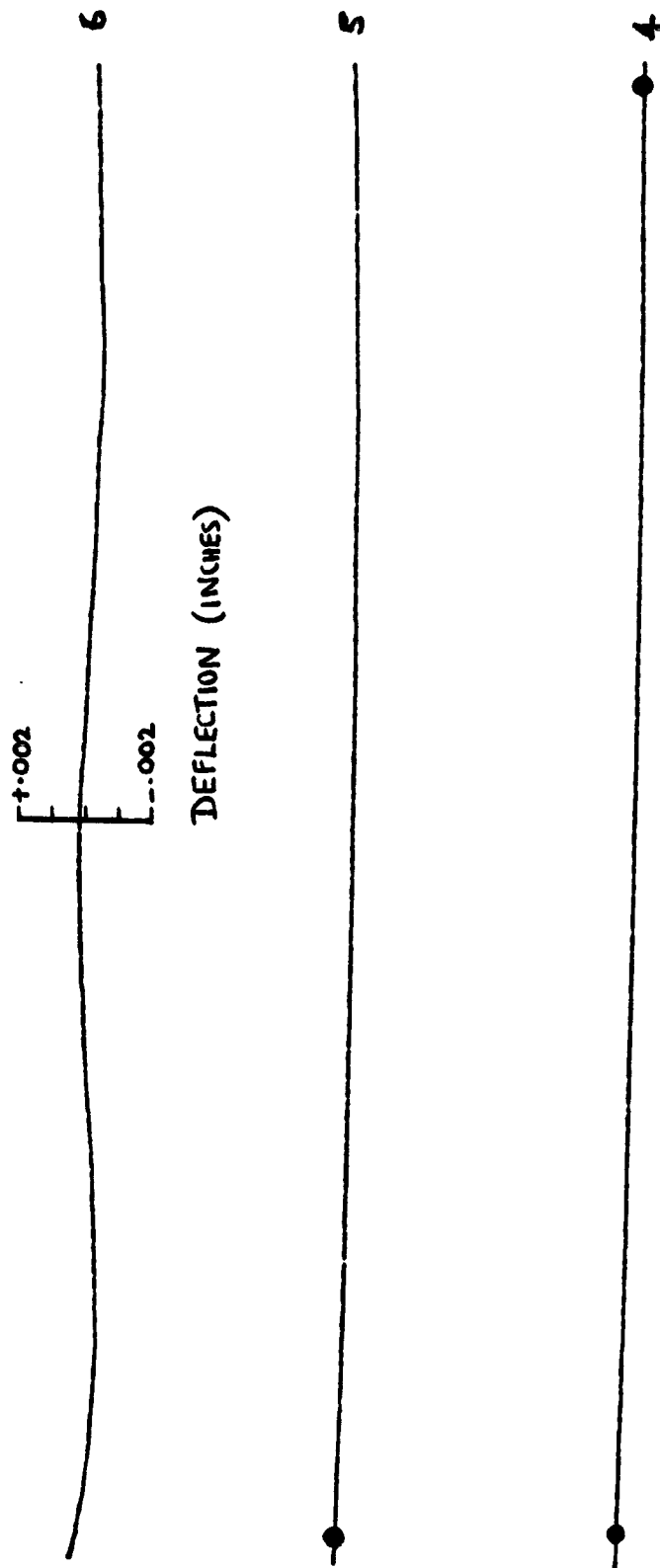


FIGURE 29. MATERIAL PH 13-8 MO SPECIMEN A-TS (TRANSVERSE, SURFACE)



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FIGURE 30. MATERIAL PH 13-8 MO SPECIMEN A-TS (TRANSVERSE, SURFACE)

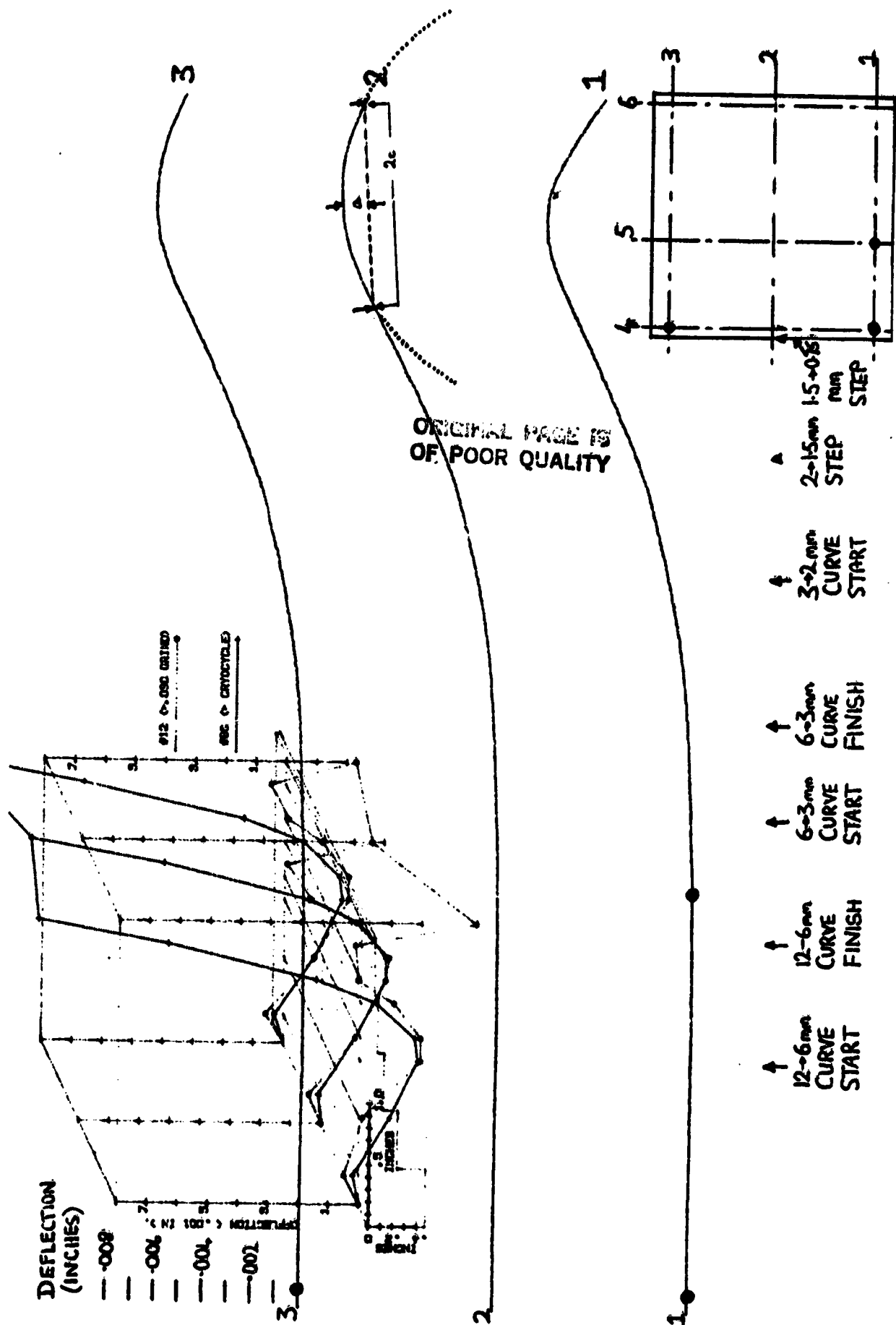


FIGURE 31. MATERIAL A286 SS SPECIMEN LS (LONGITUDINAL, SURFACE)

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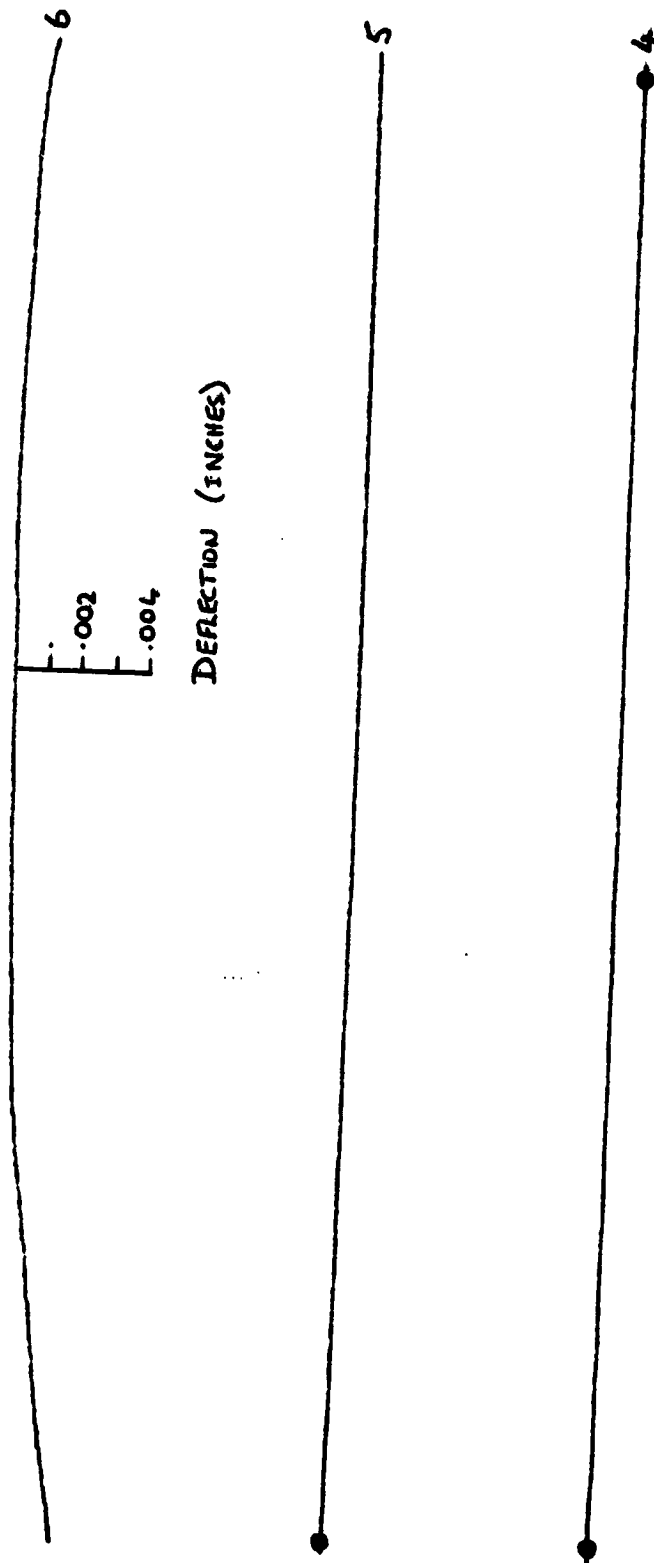


FIGURE 32. MATERIAL A286 SS SPECIMEN LS (LONGITUDINAL, SURFACE)

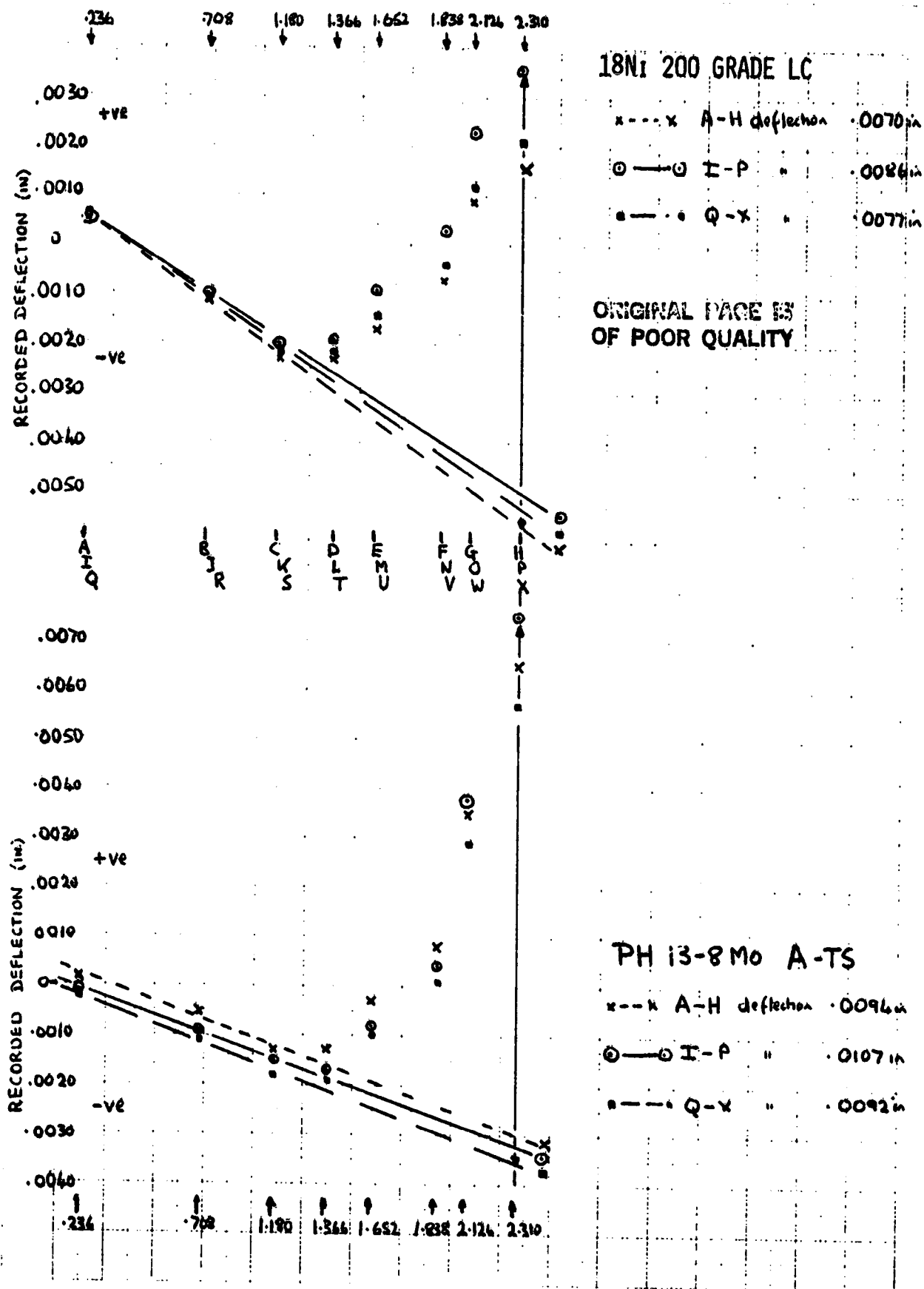


FIGURE 33. GRAPHICAL CONSTRUCTION USED TO OBTAIN TRUE END DEFLECTIONS